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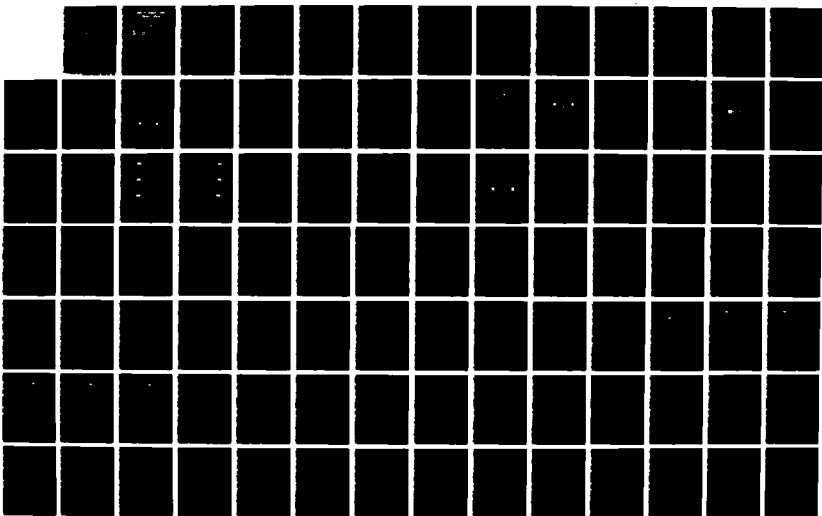　　　　　　　　NAVAL POSTGRADUATE SCHOOL MONTEREY CA　W S LEE MAR 88
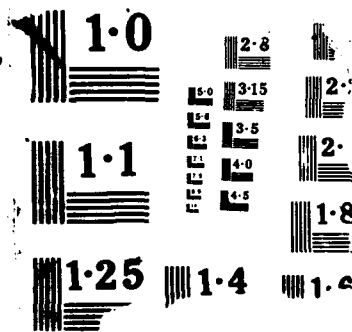
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THESIS

THE DE-EMBEDMENT OF NETWORK-ANALYZER
MEASUREMENTS

by

Whan Su Lee

March 1988

Thesis Advisor: H.A. Atwater

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The De-embedment of Network-Analyzer Measurements

by

Whan Su Lee
Major, Korean Air Force
B.S., Korean Air Force Academy, 1978

Submitted in partial fulfillment of the
requirements for the degree of

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March 1988

Author: _____
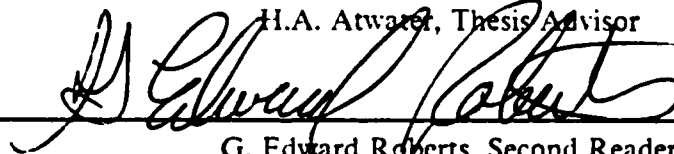
Whan Su Lee

Approved by: _____

H.A. Atwater, Thesis Advisor

_____

G. Edward Roberts, Second Reader

_____

John P. Powers, Chairman,
Department of Electrical Engineering Science

_____

Gordon E. Schacher
Dean of Science and Engineering

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ABSTRACT

In the measurement of microwave circuits and devices, the data reduction of two-port measurement data obtained at the external terminals of microstrip-coupled devices, with correction for measurement error, can be obtained by de-embedment procedures with use of the HP 8409B vector network analyzer and a Fortran program.

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I. INTRODUCTION

A. BACKGROUND

Microwave circuit elements, such as semiconductor devices, cannot be connected directly to the terminals of a microwave network analyzer for measurement of scattering or impedance coefficients but must be coupled through a chain of hardware elements comprising connector-adapters, microstrip sections, and bondwire connections. The basic problem under consideration is the removal of the effects of intervening hardware from measurements made at the external terminals of an embedded device or circuit component to obtain the intrinsic device characteristics. Accurate measurement data on a device is essential for successful circuit design.

Earlier work on device de-embedment has been coupled with undesirable restrictions such as the assumption of physical symmetry of hardware, inadequate provision for realistic measurement standards, or neglect of statistical treatment of data for improvement of accuracy. Consequently, a need exists for a practical treatment of this measurement problem which can be implemented in typical laboratory circumstances, with acceptable accuracy of results.

In order to measure the scattering parameters of a device, the device is often mounted in a fixture. This fixture has a set of scattering parameters associated with it so that the parameters measured at the terminals of the fixture are the scattering parameters of the device transformed by the embedding network of the fixture.

Thus, to obtain the scattering parameters of the device itself, the device must be "de-embedded" from the fixture. Techniques for using a network analyzer (N.A.) to de-embed the device from the test fixture have been discussed earlier [Refs. 1,2,10,11].

As long as the device interface connection is coaxial line or waveguide, de-embedding is relatively straightforward because standards are available. But if the device is constructed without a coaxial or waveguide interface, as in the case of microstrip or coplanar line systems, de-embedding becomes more difficult.

Extracting the device parameters from the overall measured parameters is strongly dependent on the ability to characterize the fixturing. Figure 1 is the block diagram and signal flow graph of a typical N.A.- fixturing setup. The problem is to find the best characterization networks A and B so as to remove their contributions, yielding the device parameters, S.

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NETWORK ANALYZER

| FIXTURE A Ⓐ | DEVICE Ⓢ | FIXTURE B Ⓑ |

DE-EMBEDDING BLOCK DIAGRAM

INPUT HALF OF FIXTURE

A21
A11 A22
A12

DEVICE

S21
S11 S22
S12

OUTPUT HALF OF FIXTURE

B21
B11 B22
B12

DE-EMBEDDING MODEL FLOW CHART
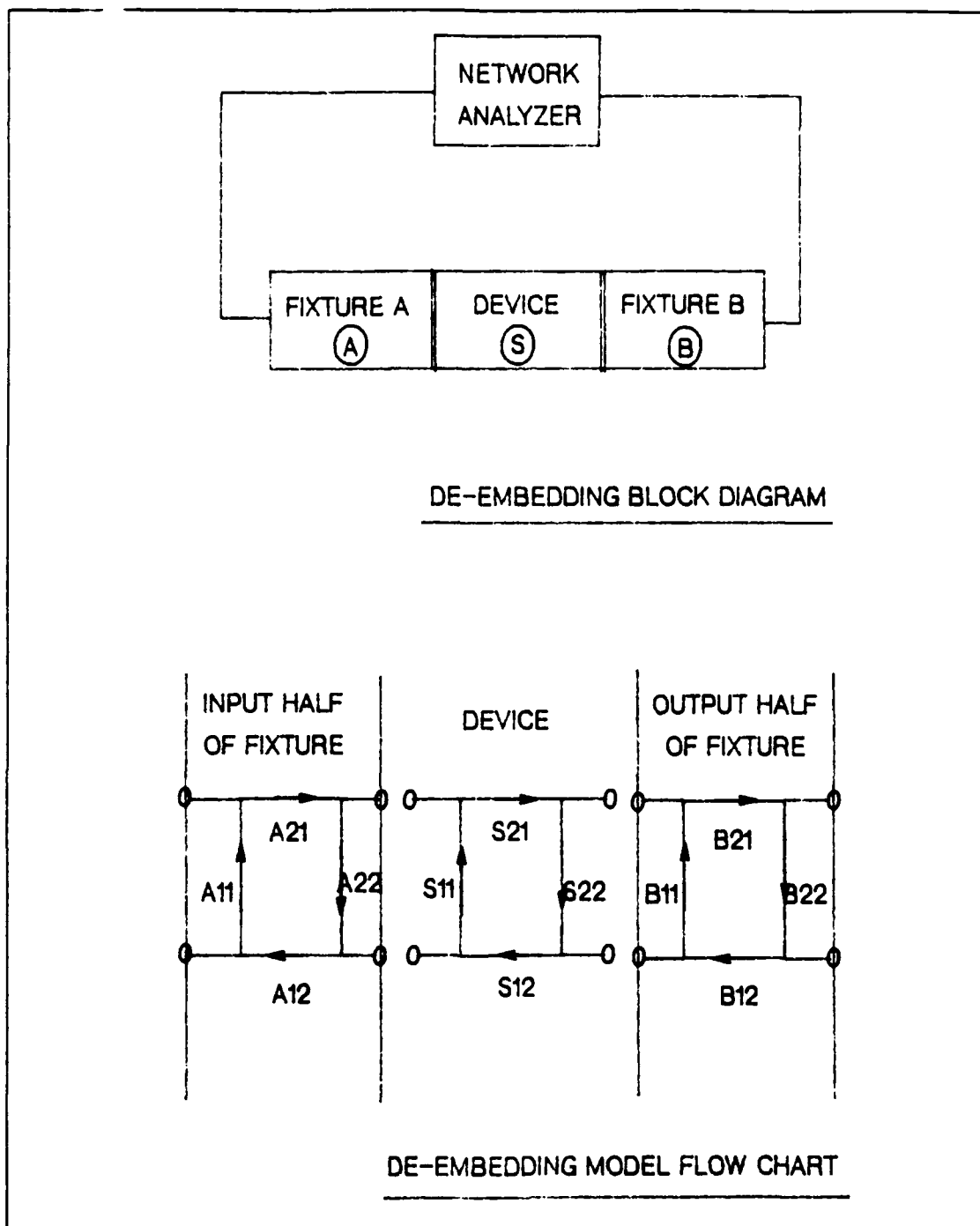
Figure 1. Block Diagram and Signal Flow Graph of a Typical Fixturing Set-up

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B. SCOPE

The scope of the proposed research will be to develop a working procedure for carrying out the removal of embedded device scattering matrices from network analyzer data. The procedure developed will be supported by experimental measurements on typical microwave circuits fabricated on planar substrates.

II. CHARACTERIZATION OF THE FIXTURES

A. CHARACTERIZATION CHOICES

Several papers present characterization techniques that are in use at various laboratories. There are four main choices of N.A.-fixturing characterization as shown Fig. 2 [Ref. 1].
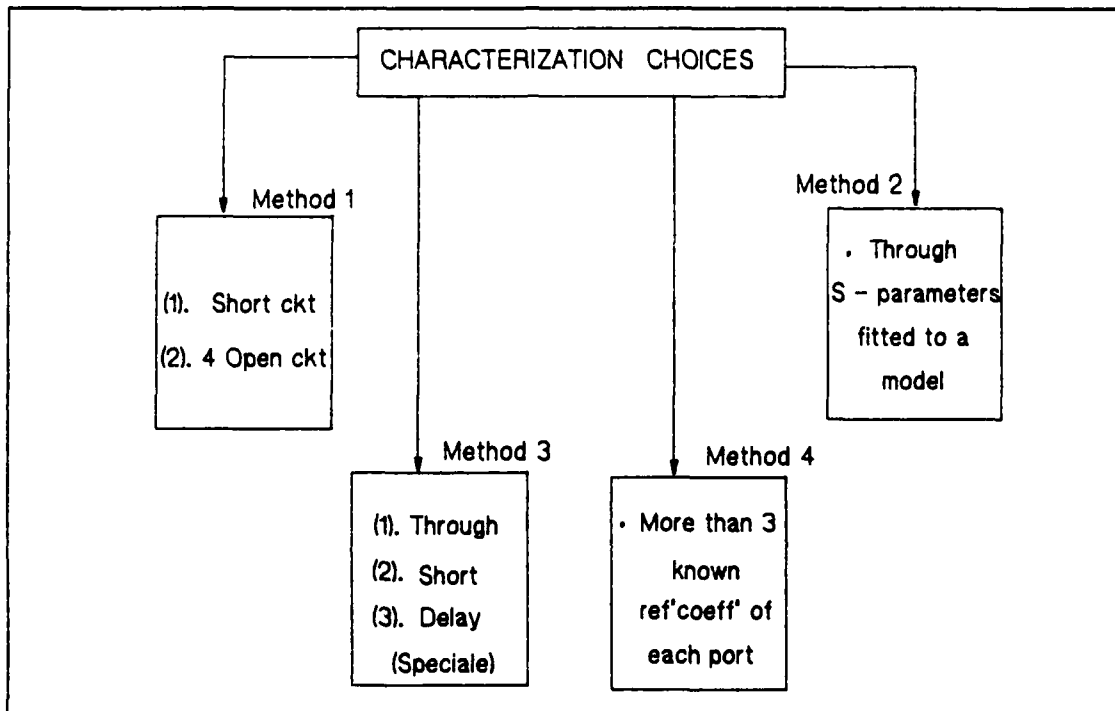
Figure 2.   The Four Main Choices of N.A.-Fixturing Characterization.

Method (1) combines a variety of measurements, including the transmission between fixtures connected back-to-back and reflection measurements on the fixtures terminated in microstrip stubs. In this way, data is assembled to enable the scattering coefficients of the embedded device to be converted to the device scattering matrix. Method (1) therefore contains features of both methods (3) and (4) below, and represents also an early example of the use of microstrip stubs as known reference standards.

In method (2), the measured S-parameters are fit to an assumed circuit model to calculate the device parameters.

Method (3) has the advantage that only three simple test pieces in the device medium are required. More details are given in Chapter V, part B.

From the above choices, method (4) was selected for investigation. In this method, three or more known reflection coefficients are measured at each port. The reference load reflection coefficients are derived from independently measured or calculated non-zero values. Reference 2 used a chip capacitor, wire bonded to microstrip on alumina, with capacitance measured at low frequency (LF). The overall reflection coefficient was then measured versus frequency. To obtain multiple calibration measurements, a piece was scribed off the chip, and the measurement cycle repeated twice more at each port.

In other cases, the reference load was a high-Q varactor chip, again measured as a function of three values of reverse bias at LF. The chip was then wire-bonded to the microstrip conductor and the overall reflection coefficients of the fixture-chip combination versus frequency were measured at each value of reverse bias.

In the present work, the reference load is a section of the microstrip line itself. Three different lengths of microstrip line yield the three different reflection coefficients for each port by separate measurements.

B. THE TEST FIXTURE

The S-parameters of the test fixture can be determined by measuring a set of known impedances in place of the embedded device. This process is known as "unterminating." Once the fixture's S-parameters have been determined, the device is measured in the calibrated test fixture, and the device parameters are "de-embedded" from the data to give an accurate picture of device performance.

The signal flow diagram and block diagram in Fig. 3 define the input and output characteristics of the test fixture.

Three sets of S-parameters must be determined when an unknown device is characterized as a two-port network mounted in a test fixture. First, the S-parameters of the input (A) and the output (B) sides of the fixture must be evaluated before the S-parameters of the device itself can be deduced. If the test fixtures are known to be symmetrical, then only one measurement is needed to determine the S-parameters of the two sides of the fixture.

In the present case, however, unsymmetrical fixtures are chosen, requiring six different measurements and calculations for both fixtures independently. To solve this problem, the input half of the fixture is first terminated at the device plane with an arbitrary load of reflection coefficient, Γ_L, followed by other loads with different reflection

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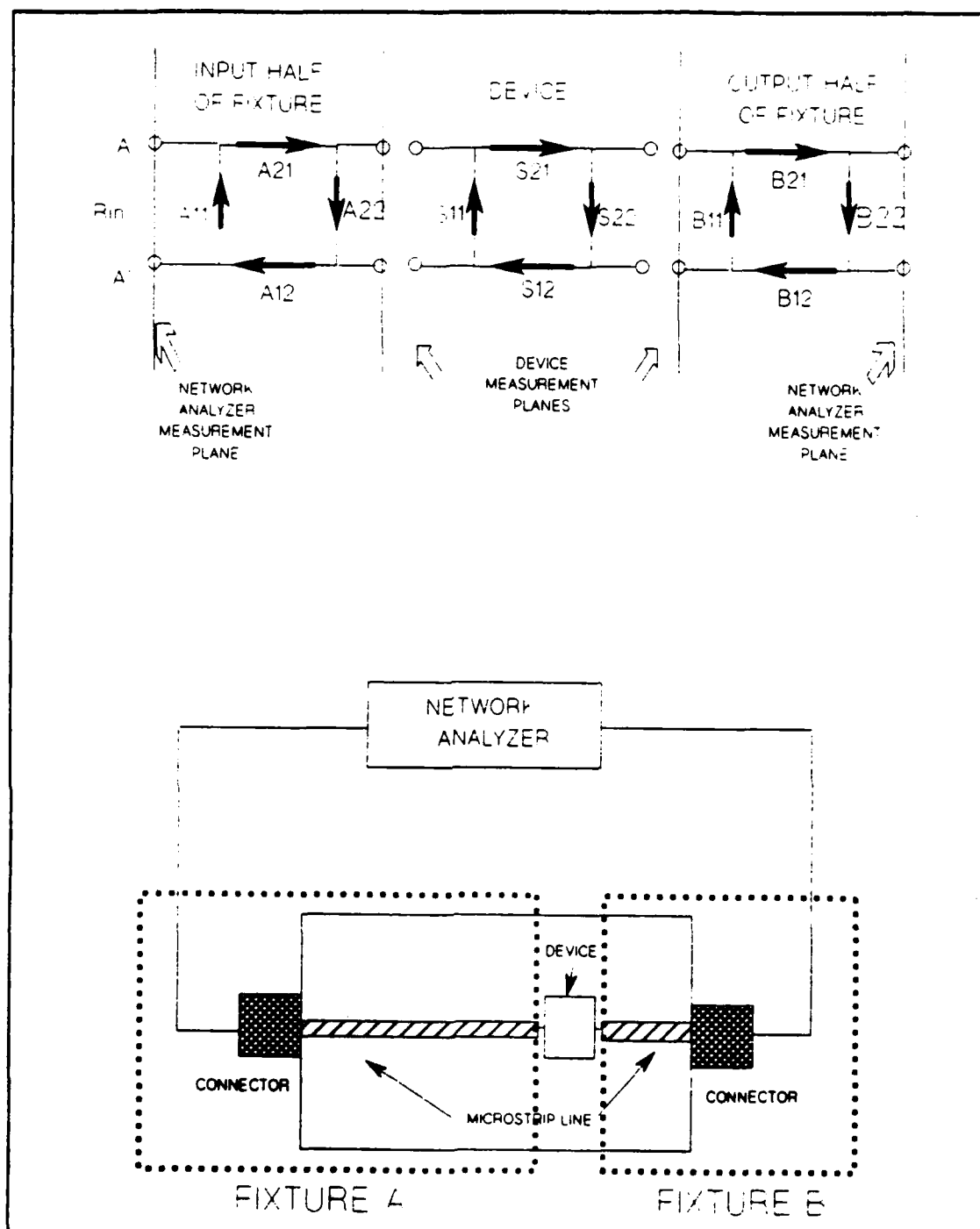
Figure 3.   The Flow Diagram and Block Diagram of the Fixture.

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coefficients. Then the output half of the fixture must also be considered with same method.
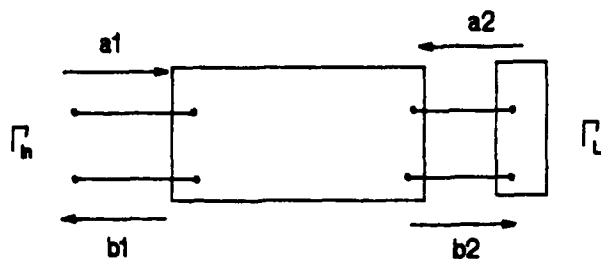
Figure 4. One Port De-Embedment

For the one port case, as shown above, the reflection coefficient is the data needed since the impedance can be calculated from it:

$$Z_L = \frac{1 + \Gamma_L}{1 - \Gamma_L} \, Z_0 \tag{2.1}$$

From the definition of the scattering matrix, the input reflection coefficient is:

$$\Gamma_{in} = \frac{b_1}{a_1} \tag{2.2}$$

$$= \frac{a_1 S_{11} + a_2 S_{12}}{a_1}$$

where, for load Γ_L,

$$a_2 = \Gamma_L b_2 \tag{2.3}$$

and

$$b_2 = S_{21} a_1 + S_{22} a_2 \tag{2.4}$$

$$= S_{21} a_1 + S_{22} (\Gamma_L b_2)$$

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Thus,

$$b_2 = S_{21} \frac{a_1}{1 - S_{22}\Gamma_L} \qquad (2.4a)$$

Using the above, we get:

$$\Gamma_{11} = S_{11} + \frac{S_{12}S_{21}\Gamma_L}{(1 - S_{22}\Gamma_L)} \qquad (2.5)$$

Here, S_{11} can be found by measuring a matched load in the fixture ($\Gamma_L = 0$). If we assume that this measurement gives $\Gamma_{in} = \Gamma_{ML}$, then we have $S_{11} = \Gamma_{ML}$. Using the result in Eq. (2.5),

$$(\Gamma_{in} - \Gamma_{ML})(1 - S_{22}\Gamma_L) = S_{12}S_{21}\Gamma_L \qquad (2.6)$$

From this,

$$S_{12}S_{21}\Gamma_L + S_{22}\Gamma_L(\Gamma_{in} - \Gamma_{ML}) = (\Gamma_{in} - \Gamma_{ML}) \qquad (2.7)$$

Two more measurements with known loads will provide enough data to determine S_{22} and $(S_{12}S_{21})$. Suppose we measure with an open-circuited load ($\Gamma_L = +1$). and a short-circuited load ($\Gamma_L = -1$). Then,

$$S_{12}S_{21} + S_{22}(\Gamma_{OC} - \Gamma_{ML}) = \Gamma_{OC} - \Gamma_{ML} \qquad (for \quad \Gamma_L = +1) \qquad (2.8)$$

$$-S_{12}S_{21} - S_{22}(\Gamma_{SC} - \Gamma_{ML}) = \Gamma_{SC} - \Gamma_{ML} \qquad (for \quad \Gamma_L = -1) \qquad (2.9)$$

These can be solved for

$$S_{22} = \frac{\Gamma_{OC} + \Gamma_{SC} - 2\Gamma_{ML}}{\Gamma_{OC} - \Gamma_{SC}} \qquad (2.10)$$

$$S_{12}S_{21} = 2 \frac{(\Gamma_{OC} - \Gamma_{ML})(\Gamma_{ML} - \Gamma_{SC})}{\Gamma_{OC} - \Gamma_{SC}} \qquad (2.11)$$

With these two quantities known, the equation for de-embedding a general unknown can be written from Eq. (2.7)

$$\Gamma_L = \frac{(\Gamma_{in} - \Gamma_{ML})}{S_{12}S_{21} + S_{22}(\Gamma_{in} - \Gamma_{ML})} \qquad (2.12)$$

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But in the actual case, it is very difficult to construct the matched load and ideal shorted and open terminations required by this procedure. Therefore, we rearrange Eq. (2.12) to matrix form for three different known loads and their reflection coefficients. From Eq. (2.5),

$$\frac{\Gamma_{in}}{\Gamma_L} = \frac{S_{11}}{\Gamma_L} + \frac{S_{12}S_{21}}{1 - S_{22}\Gamma_L}$$

$$= \frac{\frac{1}{\Gamma_L}S_{11} - S_{11}S_{22} + S_{12}S_{21}}{1 - S_{22}\Gamma_L} \tag{2.13}$$

Rearranging this gives:

$$\frac{\Gamma_{in}}{\Gamma_L} = \frac{S_{11}}{\Gamma_L} + \Gamma_{in}S_{22} - (S_{11}S_{22} - S_{12}S_{21})$$

$$= \frac{S_{11}}{\Gamma_L} + \Gamma_{in}S_{22} - \Delta \tag{2.14}$$

where,

$$\Delta \equiv S_{11}S_{22} - S_{12}S_{21}. \tag{2.15}$$

This equation then involves the three unknowns S_{11}, S_{22}, and Δ. These three unknowns can be determined by making three independent measurements of Γ_{in} with three different known loads. In matrix form, the problem can be expressed as:

$$\begin{bmatrix} \dfrac{1}{\Gamma_{L1}} & \Gamma_{in1} & -1 \\[2mm] \dfrac{1}{\Gamma_{L2}} & \Gamma_{in2} & -1 \\[2mm] \dfrac{1}{\Gamma_{L3}} & \Gamma_{in3} & -1 \end{bmatrix} \begin{bmatrix} S_{11} \\[2mm] S_{22} \\[2mm] \Delta \end{bmatrix} = \begin{bmatrix} \dfrac{\Gamma_{in1}}{\Gamma_{L1}} \\[2mm] \dfrac{\Gamma_{in2}}{\Gamma_{L2}} \\[2mm] \dfrac{\Gamma_{in3}}{\Gamma_{L3}} \end{bmatrix} \tag{2.16}$$

To find S_{11}, S_{22} and Δ, solve:

$$\begin{bmatrix} S_{11} \\ \\ S_{22} \\ \\ \Delta \end{bmatrix} = \begin{bmatrix} \dfrac{1}{\Gamma_{L1}} & \Gamma_{in1} & -1 \\ \dfrac{1}{\Gamma_{L2}} & \Gamma_{in2} & -1 \\ \dfrac{1}{\Gamma_{L3}} & \Gamma_{in3} & -1 \end{bmatrix}^{-1} \begin{bmatrix} \dfrac{\Gamma_{in1}}{\Gamma_{L1}} \\ \dfrac{\Gamma_{in2}}{\Gamma_{L2}} \\ \dfrac{\Gamma_{in3}}{\Gamma_{L3}} \end{bmatrix} \qquad (2.17)$$

Γ_{L1}, Γ_{L2} and Γ_{L3} are three different calculated reflection coefficients at the terminals of the three different loads. Also, Γ_{in1}, Γ_{in2} and Γ_{in3} are three reflection coefficients measured from the N.A. with respect to the three different loads. Now the problem requires accurate values of Γ_{L1}, Γ_{L2}, Γ_{L3} and Γ_{in1}, Γ_{in2}, Γ_{in3}. We consider in the next chapter the computation of Γ_{L1}, Γ_{L2} and Γ_{L3} for reference microstrip line loads.

III. MICROSTRIP LINE FOR THE FIXTURE

A. MICROSTRIP LINE

The definition of an effective relative dielectric constant, ε_{re}, allows us to treat microstrip line like a TEM system. Relations between line and freespace parameters then hold (which are typical of TEM systems). With ε_{re} replacing the conventional relative dielectric constant,

$$\frac{\lambda_{ms}}{\lambda_0} = \frac{1}{\sqrt{\varepsilon_{re}}} \tag{3.1a}$$

$$\frac{v_{ms}}{c} = \frac{1}{\sqrt{\varepsilon_{re}}} \tag{3.1b}$$

$$\frac{Z_0}{Z_{0air}} = \frac{1}{\sqrt{\varepsilon_{re}}} \tag{3.1c}$$

$$\frac{1}{v_{ms}C_{ms}} = v_{ms} L_{ms} \tag{3.1d}$$

where λ_{ms} and v_{ms} are the wavelength and velocity of the waves on the microstrip line and λ_0 and c are the free space values at the frequency of operation.

In Eqs. (3.1), L_{ms} and C_{ms} are the inductance and capacitance per unit length of the microstrip line. Z_0 is its characteristic impedance, and Z_{0air} is the value Z_0 would have if the dielectric layer were replaced by air. To the lowest order of approximation, the value of ε_{re} would be the average of the relative dielectric constant of the substrate and that of air, namely:

$$\varepsilon_{re} = \frac{1 + \varepsilon_r}{2} \tag{3.2}$$

More exact values have been obtained, largely through solutions of the quasistatic model, corrected to match measured data.

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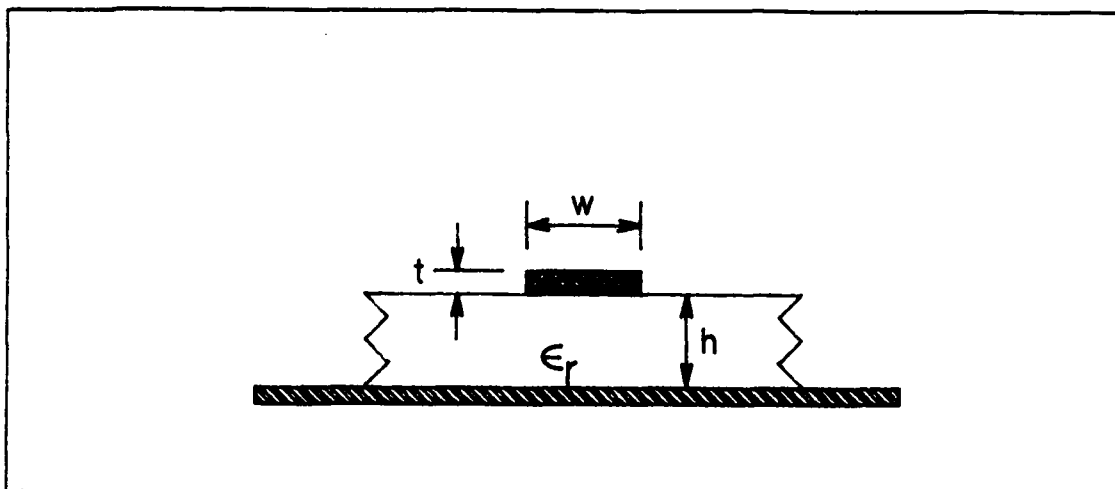
Figure 5. Microstrip Line Dimensions.

In case of lines with line width ratio $u \equiv \dfrac{w}{h} = 0.1$ to 10,

$$\varepsilon_{re}(0) = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[\frac{1}{\sqrt{1 + \dfrac{12.35}{u}}} + 0.06(1 - u)^2 e^{-0.44u\varepsilon_r} \right] \qquad (3.3)$$

If microstrip were a true TEM system, the velocity of waves on the line, the impedance Z_0 and other line parameters would be independent of frequency. The quasistatic or zero frequency values of the parameters are good approximations at frequencies up to the order of a few gigaherz. When the wavelength becomes comparable with the cross sectional dimensions of the line, v_{ms} and the line parameters are no longer frequency independent. Therefore, dispersion of effective relative dielectric constant is

$$\varepsilon_{re}(f) = \varepsilon_r - \left[\frac{\varepsilon_r - \varepsilon_{re}(0)}{1 + \dfrac{\varepsilon_{re}(0)}{\varepsilon_r}\left(\dfrac{2h\mu_0 f}{Z_0}\right)^2} \right] \qquad (3.3a)$$

where h is the substrate height, f is frequency and μ_0 is the permeability of free space.

B. MICROSTRIP STUB-RESONANCE EVALUATION OF DIELECTRIC CONSTANT

It was necessary to determine the substrate dielectric constant ε_r of the microstrip line substrates used for measurements in the present work.

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The steps are:

1. Measure the resonant frequency of a quarter wave length stub. (Substrate height is h = 1.5 mm, line width ratio u = 3.0 (where u = w / h)),
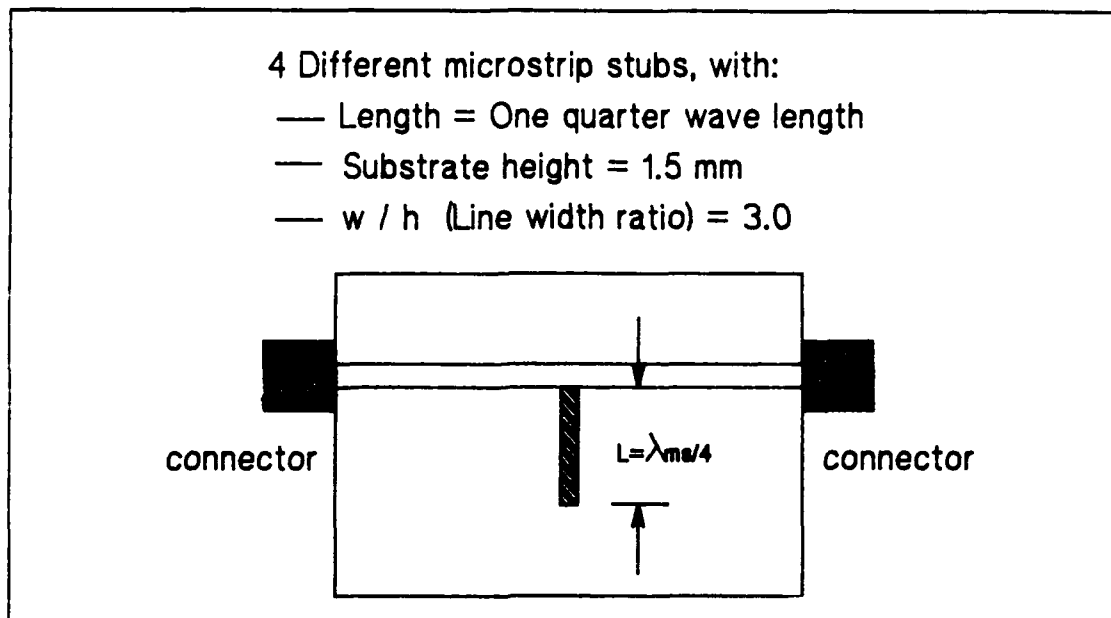
Figure 6. Measurement Setup for Dielectric Constant Measurement

2. Measure the value of S_{21}, transmission coefficient, with respect to frequency using the N.A.,

3. Find the frequency (f_0) at which maximum dB transmission loss due to resonance occurs, as shown in Fig. 7,
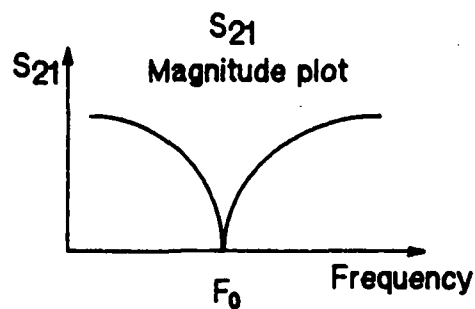
Figure 7. Determination of the Max. dB Loss Point.

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4. Calculate ε_{re} from Eq. (3.1a). It is normally required to account for the fringing capacitance at an open microstrip termination. Computation by standard methods [Ref. 3: p. 138] showed that the open-end length correction was less than 1.0% for stub lengths greater than 50 mm. This had negligible effect on the calculated ε_{re} and was neglected.

$$\lambda_0 = \lambda_{ms}\sqrt{\varepsilon_{re}} \tag{3.4}$$

$$v_{ms} = \frac{c}{\sqrt{\varepsilon_{re}}} \tag{3.5}$$

$$= f_0\lambda_{ms}$$

therefore,

$$\lambda_{ms} = \frac{c}{f_0\sqrt{\varepsilon_{re}}} \tag{3.6}$$

where

$$\lambda_{ms} = 4l.$$

From the equations above,

$$\varepsilon_{re} = (\frac{c}{4lf_0})^2 \tag{3.7}$$

Through the several measurements as shown in Table 1, the average ε_{re} obtained by calculation has the value of 2.833.,

Table 1. THE MEASUREMENT OF EFFECTIVE RELATIVE DIELECTRIC CONSTANT

Length (mm)	$f_0(GHz)$	ε_{re}
98.0	0.452	2.867
80.0	0.564	2.763
60.0	0.746	2.808
40.0	1.102	2.895

5. From stub resonance data, the corresponding ε_{re} is calculated. Eq. (3.3) was inverted by trial and error to find $\varepsilon_r = 3.516$ from the experimental ε_{re}.

C. CHARACTERISTIC IMPEDANCE OF MICROSTRIP LINE

Expressions for the characteristic impedance of microstrip lines have been developed through numerous successive approximations, based principally on TEM models having the specific microstrip line cross section, with correction terms added to obtain agreement with experimental observation.

$$Z_0 = \frac{60}{\sqrt{\varepsilon_{re}}} \ln\left[\frac{(0.99u + 1.795)(0.994u + 5.80)}{u(u + 1.268)} \right] \qquad (3.8)$$

where the synthesis formula for linewidth ratio u = w/h is:

$$u = \frac{w}{h} = \frac{8}{A} \sqrt{A(0.647 + \frac{0.4116}{\varepsilon_r}) + 1.321(1 + \frac{1}{\varepsilon_r})} \qquad (3.9)$$

with

$$A \equiv \left[\exp(Z_0 \frac{\sqrt{2(\varepsilon_r + 1)}}{60}) - 1 \right] \qquad (3.10)$$

From Eqs. 3.3, 3.6 and 3.8, one can easily get the characteristic impedance for each microstrip section. For example, for the given characteristic impedance of 50 Ω, the microstrip line width ratio is u = 2.283 and the width is 3.43 mm. In the construction of microstrip stub loads, it is necessary to choose high characteristic impedance for accurate measurement, since high impedance leads to narrow linewidth and a well-defined point of attachment of the stub. Construction problems arise in making microstrip line with very small width. For example, if we want to make a microstrip line stub of 90 Ω *characteristic impedance*, the required width is about 1.2 mm for given h = 1.5 mm. It is difficult to handle the adhesive foil material used for the microstrip itself. For this reason, a compromise value was chosen, using 2.0 mm width of microstrip stub for given substrate height h = 1.5 mm. Then,

$h = 1.5mm$

$w = 2.0mm$

also $u = \frac{w}{h} = 1.33.$

Therefore,

$Z_{0s} = 68.2\Omega,$

which was chosen as a working value for stub impedance.
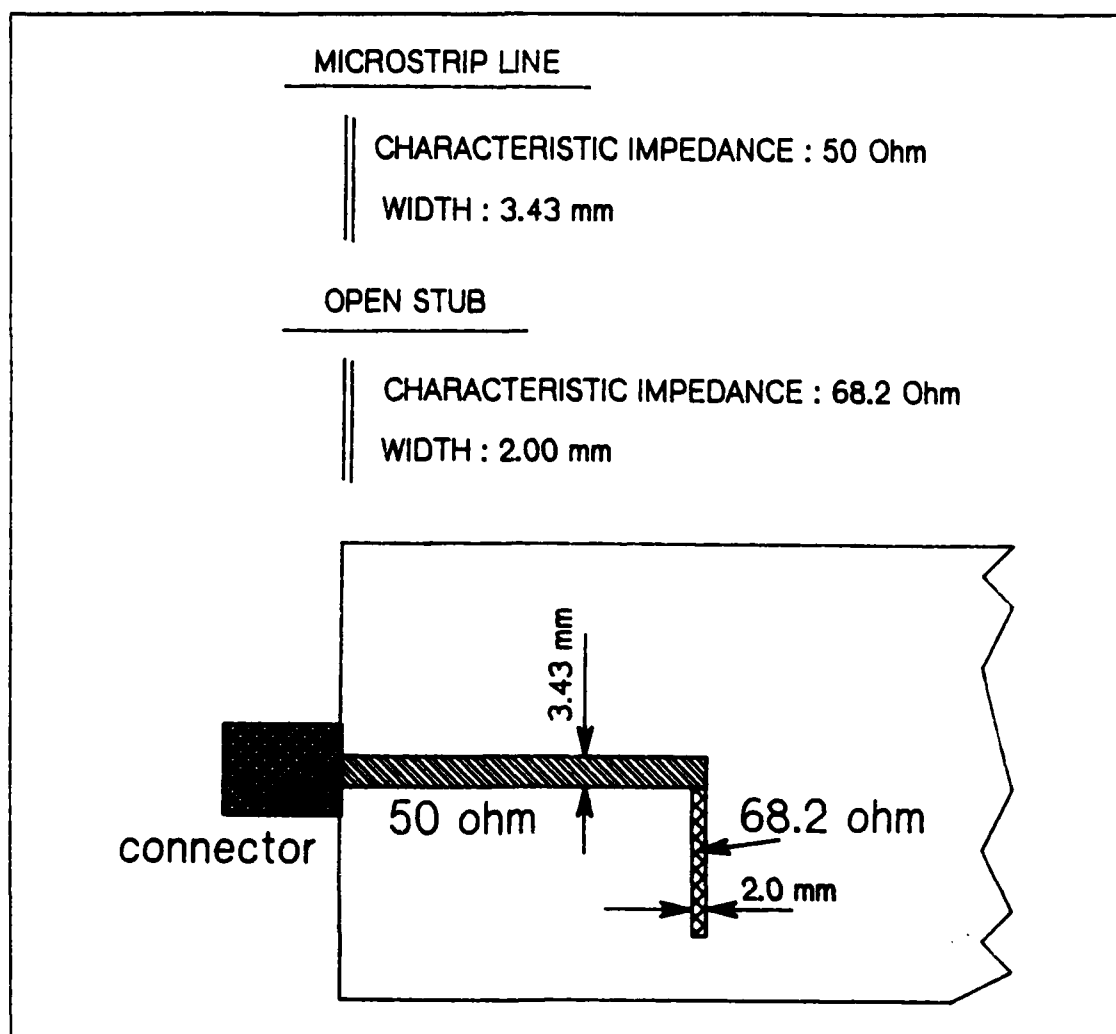
Figure 8.   Experimental Setup for Characterization of the Fixture

D. STUB LOAD IMPEDANCE AND REFLECTION COEFFICIENT

Consider the transmission-line impedance-transformation law:

$$Z_{in} = Z_{0s} \left[\frac{Z_L \cos \beta l + j Z_{os} \sin \beta l}{Z_{0s} \cos \beta l + Z_L \sin \beta l} \right] \tag{3.11}$$

From Eq. (3.11), when Z_L goes to ∞ (open ended), the input impedance of an open - ended stub becomes:

$$Z_{in} = Z_{0s} \left[\frac{\cos \beta l}{j \sin \beta l} \right]$$

$$= -jZ_{0s} \cot(\beta l)$$

(3.12)

using

$$\beta = \frac{2\pi}{\lambda}$$

(3.13)

$$\lambda = \frac{v}{f}$$

$$= \frac{c}{f\sqrt{\varepsilon_{re}}}$$

(3.14)

Therefore,

$$Z_L = -jZ_{0s} \cot \left[\frac{2\pi f l \sqrt{\varepsilon_{re}}}{c} \right]$$

$$= -jZ_{0s} \frac{\cos \left[\frac{2\pi f l \sqrt{\varepsilon_{re}}}{c} \right]}{\sin \left[\frac{2\pi f l \sqrt{\varepsilon_{re}}}{c} \right]}$$

(3.15)

Once the Z_{0s} is chosen, we can determine the load impedance of three different loads. For example, given $Z_{0s} = 68.2$ ohms and microstrip line lengths of 4 cm, 3 cm, 2 cm, the load impedances are tabulated as shown Table 2.

Table 2.   THE LOAD IMPEDANCE OF REFERENCE STUB LOADS

Frequency(GHz)	L = 4 cm (Z_{L1})	L = 3 cm (Z_{L2})	L = 2 cm (Z_{L3})
1.00	-j 11.06	-j 38.44	-j 80.15
2.00	j 204.8	j 41.28	-j 11.06
3.00	-j 35.69	-j 1230	j 41.28
4.00	j 91.05	-j 35.69	j 204.81
5.00	-j 70.73	j 44.23	-j 168.99

The three different reflection coefficients of the given arbitary loads are:

$$\Gamma_{Li} = \frac{Z_{Li} - Z_0}{Z_{Li} + Z_0}$$
(3.16)

where $i = 1, 2, 3$. Therefore, from the given stub impedances and $Z_0 = 50\Omega$, the reflection coefficients are tabulated in Table 3.

Table 3. THE STUB REFLECTION COEFFICIENTS

Freq.(GHz)	L = 4 cm (Γ_{L1})	L = 3 cm (Γ_{L2})	L = 2 cm (Γ_{L3})
1.00	-0.91 - j0.42	-0.26 - j0.97	0.44 - j0.90
2.00	0.89 + j0.46	-0.19 + j0.98	-0.91 - j0.42
3.00	-0.32 - j0.95	1.00 - j0.05	-0.19 + j0.98
4.00	0.54 + j0.84	-0.32 - j0.95	0.89 + j0.46
5.00	0.33 - j0.94	-0.12 + j0.99	0.84 - j0.54

IV. APPLICATION OF THE DE-EMBEDDING PROCEDURE

A. MEASUREMENT OF THE EMBEDDING FIXTURE

The reflection coefficients required are measured by the HP 8409B vector network-analyzer. One can find the reflection coefficient, Γ_m, of the stub terminated fixtures by measurement of the scattering matrix element S_{11} using the network-analyzer. The outputs of the N.A. represent the magnitude (dB loss) and phase angle (degrees) of S_{11}. Therefore, the outputs of the N.A. must be changed to complex notation using the simple modification:

$$\Gamma_{in} = (10)^{\frac{-S_{11dB}}{20}} \cos(\arg S_{11}) + j(10)^{\frac{-S_{11dB}}{20}} \sin(\arg S_{11}). \tag{4.1}$$

The outputs of the N.A. and Γ_{in} are obtained for each load on one fixture (A) as shown in Figs. 9-a to 9-c. When we consider the other fixture (B), all steps are exactly same as for fixture A except the fixture shape itself, shown in Figs. 10-a to 10-c. Tables for fixture A and fixture B data are available in Appendix A.

B. S-PARAMETERS OF THE FIXTURE

To consider the de-embedding calculation, we return to the original matrix equation. The success of this characterization technique depends heavily on the measurement of the load impedances used in the unterminating process for the fixtures. Once an input reflection coefficient has been measured with three different impedance standards, the S-parameters of the test fixture can be computed using the matrix introduced earlier. A word of caution must be offered about the convergence of this apparently simple problem.

The matrix that must be inverted consists of elements very near unity, a situation often used to illustrate some of the numerical inversion methods. In this case, the Gauss-Jordan method with full pivoting is recommended. Pivoting improves the stability of the numerical solution by interchanging rows and columns in the Gaussian elimination. In the notation of Eq. (2.17), the scattering parameter S_{ij} is changed to A_{ij} and B_{ij} for fixture A and B (respectively):

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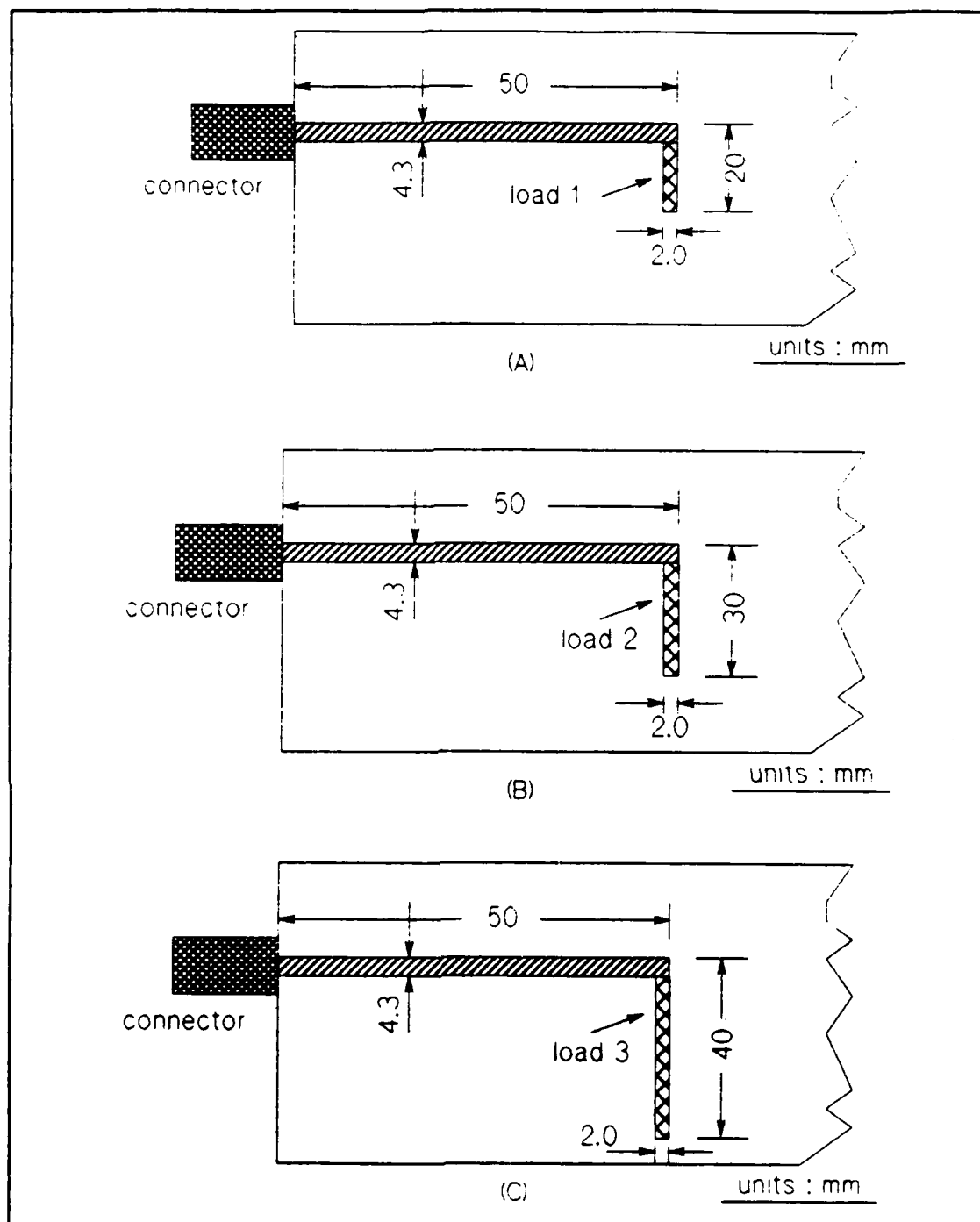
Figure 9. Measurement of the Load for Fixture A

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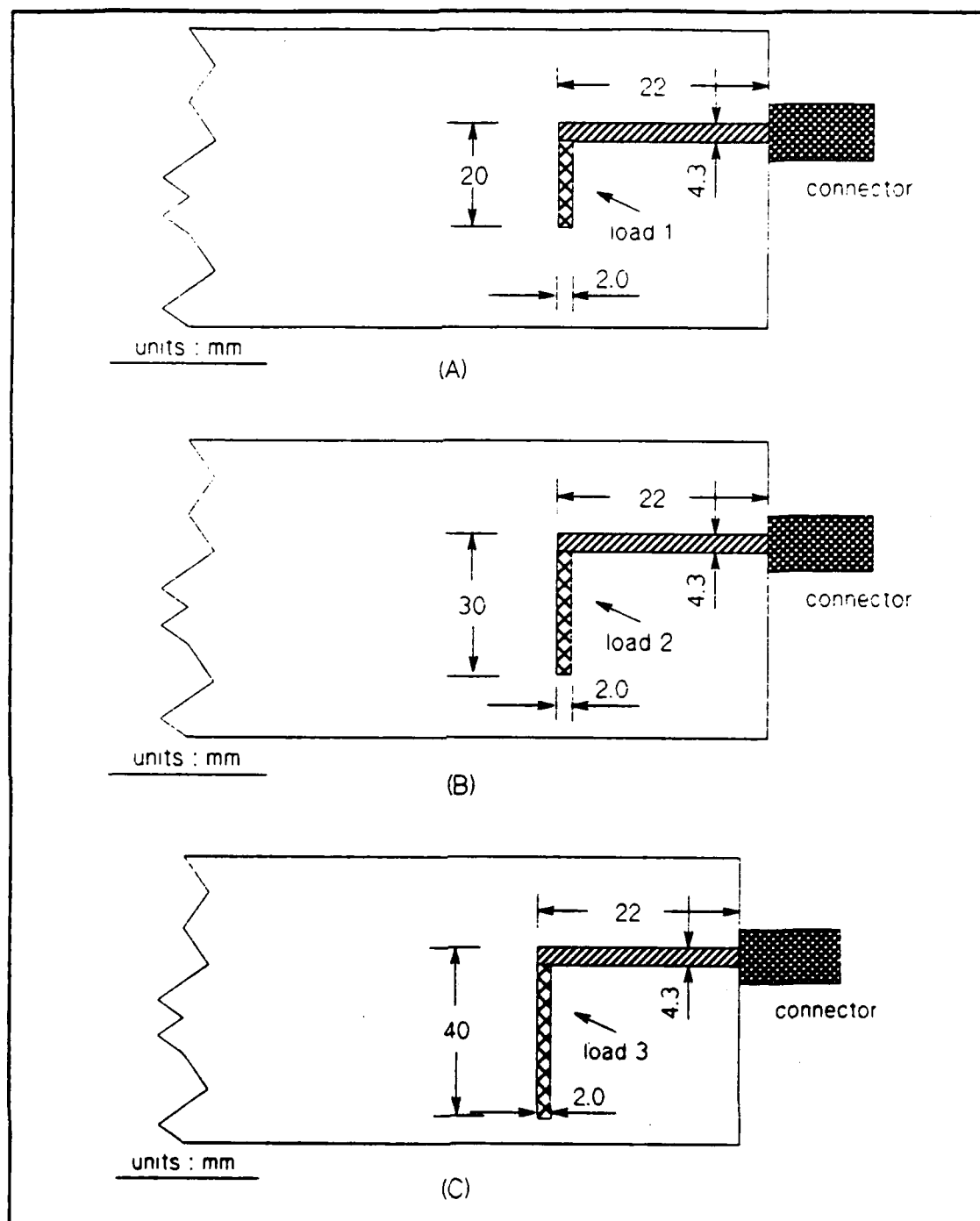
Figure 10. Measurement of the Load for Fixture B

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$$
\begin{bmatrix} A_{11} \\ A_{22} \\ \Delta \end{bmatrix} = \begin{bmatrix} \dfrac{1}{\Gamma_{L1}} & \Gamma_{in1} & -1 \\ \dfrac{1}{\Gamma_{L2}} & \Gamma_{in2} & -1 \\ \dfrac{1}{\Gamma_{L3}} & \Gamma_{in3} & -1 \end{bmatrix}^{-1} \begin{bmatrix} \dfrac{\Gamma_{in1}}{\Gamma_{L1}} \\ \dfrac{\Gamma_{in2}}{\Gamma_{L2}} \\ \dfrac{\Gamma_{in3}}{\Gamma_{L3}} \end{bmatrix}
\tag{4.2}
$$

where

$$
\Delta \equiv A_{11}A_{22} - A_{12}A_{21}.
\tag{4.3}
$$

The computed values for A_{11} and A_{22}, combined with a knowledge of Δ, can be used to determine the $A_{12}\,A_{21}$ product. Note that the fixture is reciprocal, so $A_{12} = A_{21}$ and for the other fixture, $B_{12} = B_{21}$. Thus, the magnitudes of these terms can be calculated by taking the square root of the product term in the expression for Δ.

The question of phase is left open, but is not essential. Since the A_{12}, A_{21}, B_{12} and B_{21} terms always appear in product form, it does not matter which of the two possible phase angles one chooses, as long as the phase angles for A_{21} and B_{21} are approximately the same. All of these calculations are shown in Appendix E using the Fortran program shown. This program combines the measurement and calculated values, that is, the outputs of the N.A. are used in the calculation as a form of datafile. The resulting S-parameters of these fixtures are shown in Appendix B.

C. DE-EMBEDDING PROCEDURE

1. Background

When a two-port network is connected between fixture A and B, the signal flow graph for the system may be drawn as shown in Fig. 11. Parameters AB and BA are mainly contributed by the finite isolation of the internal switches of the network analyzer. The terms S_{11}, S_{21}, S_{12}, and S_{22} are the scattering parameters of the device under test. The fixture parameters, A_{11}, A_{21}, A_{12} and A_{22}, can be determined by reflection measurements at port 1, as discussed earlier. Parameters B_{22}, B_{11} and $B_{12}B_{21}$ can be evaluated by similar measurements at port 2. Two port transmission measurements with the device under test replaced by a through-line are used for evaluating parameters AB and BA, and products $A_{21}B_{21}$ and $A_{12}B_{12}$. When a through-line of length l, having zero reflections at both ends and a transmission $T = e^{-j\beta l}$, is connected between the two ports, the signal-flow graph of Fig. 11 can be simplified to the one shown in Fig. 12.

22
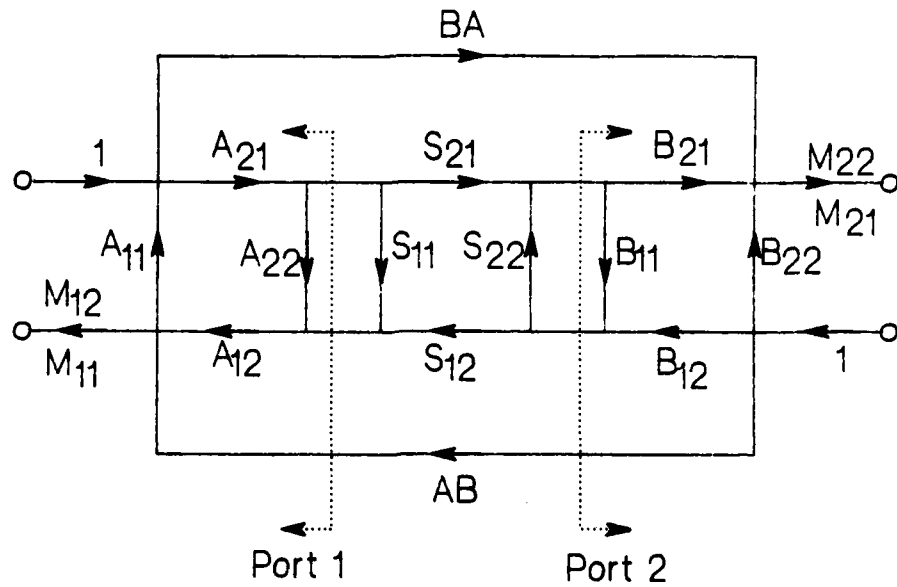
Figure 11. Signal Flow Graph for Measurements on a Two - Port Network

The measured transmission T_m can be expressed as

$$T_m = BA + \frac{A_{21}B_{21}T}{1 - A_{22}B_{11}T^2} \tag{4.4}$$

When the error parameters A_{22} and B_{11} have been determined by the reflection measurements, two transmission measurements must be performed for the determination of BA and $A_{21}B_{21}$. The value of BA can be found by making a transmission measurement when no connection exists between the ports (that is T = 0). The parameter $A_{21}B_{21}$ can be determined from the measurement of a through - line using

$$A_{21}B_{21} = \frac{(T_m - BA)(1 - A_{22}B_{11}e^{-j2\beta l})}{e^{-j\beta l}} \tag{4.5}$$

where $T = e^{-j\beta l}$, jβ being the propagation constant of the through-line. The error parameters AB and $A_{12}B_{12}$ can be determined by making a similar measurement.

Now that the scattering characteristics of the embedding networks have been measured, the scattering parameters M_{11}, M_{22}, M_{12} and M_{21} can be corrected for the em-

23
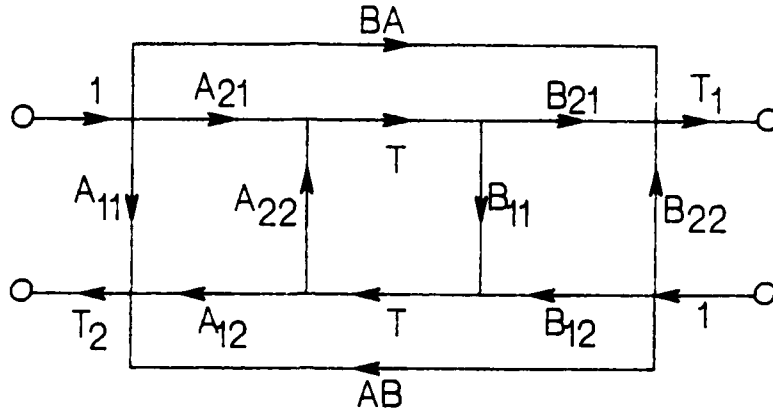
Figure 12. Signal Flow Graph with a Through - Line

bedding networks to obtain S_{11}, S_{22}, S_{12} and S_{21}. Elements M_{ij} represent the scattering parameters of both fixtures and device, namely:

$$M_{11} = A_{11} + \frac{S_{11}A_{12}A_{21}(1 - S_{22}B_{11}) + (S_{21}S_{12}B_{11}A_{12}A_{21})}{D} \tag{4.6}$$

$$M_{21} = BA + \frac{S_{21}B_{21}A_{21}}{D} \tag{4.7}$$

$$M_{22} = B_{22} + \frac{S_{22}B_{21}B_{12}(1 - S_{11}A_{22}) + (S_{21}S_{12}A_{22}B_{12}B_{21})}{D} \tag{4.8}$$

$$M_{12} = AB + \frac{S_{12}B_{12}A_{12}}{D} \tag{4.9}$$

where

$$D = 1 - S_{11}A_{22} - S_{22}B_{11} - S_{12}S_{21}A_{22}B_{11} + S_{22}S_{11}A_{22}B_{11} \tag{4.10}$$

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These equations must be inverted to extract the scattering parameters S_{ij}. An explicit solution for the scattering parameters of the device under test has been presented in Ref. [4] : p. 313 . The solution is as follows:

$$S_{11} = \frac{G(1 + B_{11}H) - B_{11}EF}{N} \tag{4.11}$$

$$S_{12} = \frac{E}{N} \tag{4.12}$$

$$S_{21} = \frac{F}{N} \tag{4.13}$$

$$S_{22} = \frac{H(1 + A_{22}G) - A_{22}EF}{N} \tag{4.14}$$

where

$$N = (1 + A_{22}G)(1 + B_{11}H) - A_{22}B_{11}EF \tag{4.15}$$

$$E1 = \frac{(M_{12} - AB)}{(A_{12}B_{12})} \tag{4.16}$$

$$F1 = \frac{(M_{21} - BA)}{(A_{21}B_{21})} \tag{4.17}$$

$$G = \frac{(M_{11} - A_{11})}{(A_{12}A_{21})} \tag{4.18}$$

$$H = \frac{(M_{22} - B_{22})}{(B_{12}B_{21})} \tag{4.19}$$

In the present measurement, inclusion of the leakage paths BA and AB is not necessary because of the one-port calibration procedure used. Therefore, Eqs. (4.16, 4.17) are:

$$E = \frac{M_{12}}{A_{12}B_{12}} \tag{4.16a}$$

$$F = \frac{M_{21}}{A_{21}B_{21}} \tag{4.17a}$$

Some variations of the above calibration procedure are available in Ref. [4] : p. 315 .

The de-embedding procedure used in this work is based on Eqs. (4.11 to 4.15) and Eqs. (4.16a, 4.17a, 4.18 and 4.19) which use the 9 key parameters:

$$S_{11}, \ S_{12}, \ S_{21}, \ S_{22}, \ E, \ F, \ G, \ H, \ N$$

and the foregoing derivations. The complete block diagram is shown in Fig. 14. If we know A_{ij} and B_{ij}, the scattering parameters of fixtures A and B, and the parameters of both fixtures plus device, M_{ij}, then the scattering parameters of the device itself are obtained by using Eqs. 4.11 to 4.14. In order to test the de-embedding procedure, consider the set up of Fig. 13.
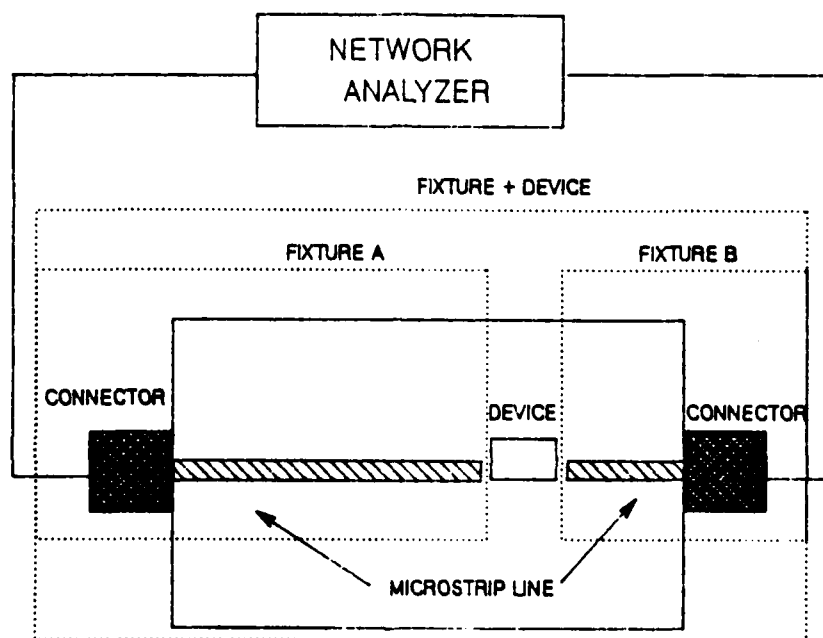
Figure 13. **Device and Fixture Assembly for the 51 Ohm Resistor**

It is necessary to choose a device that has known scattering parameters; then it will be possible to compare the output of the de-embedding experiment with the theoretical parameters of device itself. The initial test object is a series-connected 51 Ohm resistor which has a small inductance so that the impedance of the 51 Ohm device is:

$$Z = R + j\omega L$$
$$= 51 + j2\pi f L \tag{4.20}$$

where we may assume the parasitic inductance associated with the resistor to be
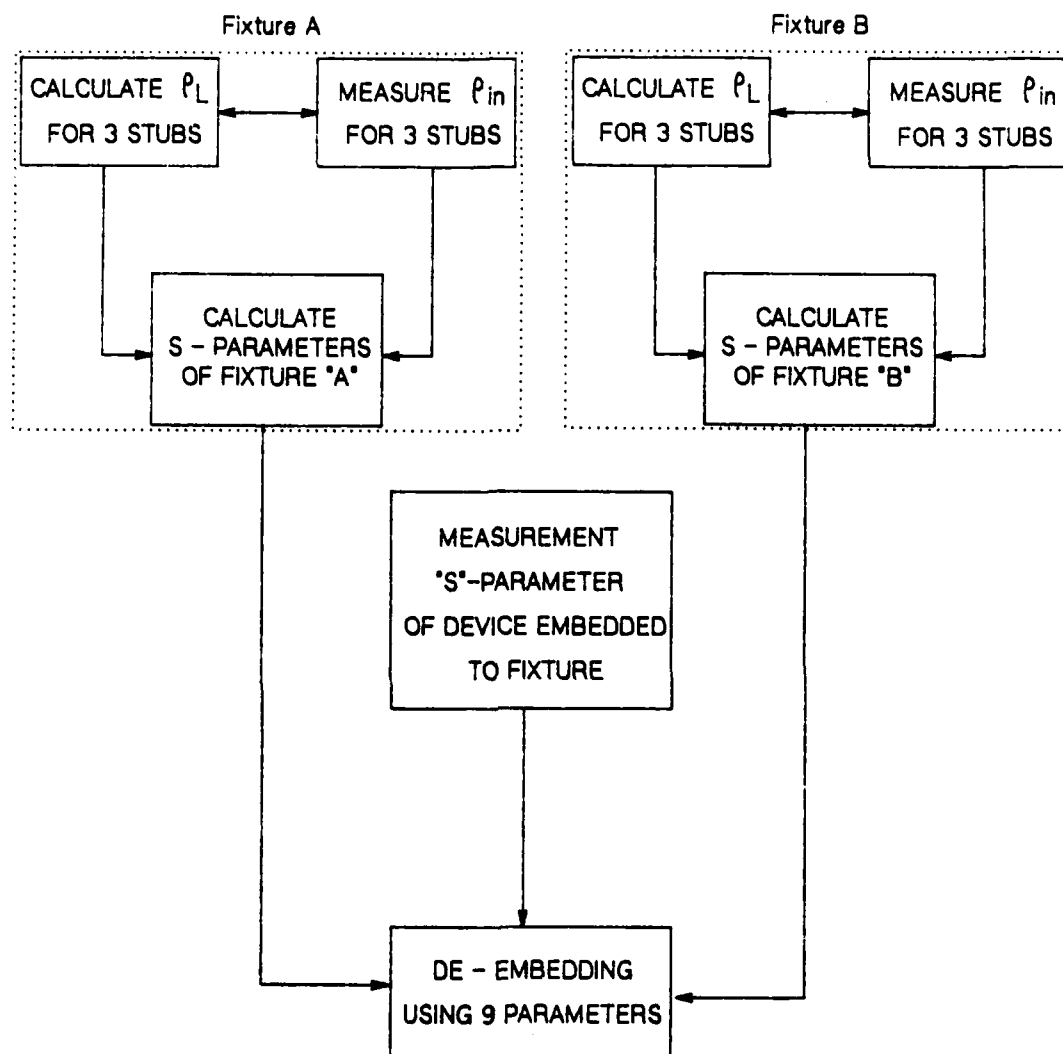
Figure 14.   The Block Diagram of the De-Embedding Procedure

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$L = 2.5\,nH.$

The scattering matrix of an impedance Z connected in series with the transmission line is :

$$S = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} = \begin{bmatrix} \dfrac{z}{2+z} & \dfrac{2}{2+z} \\[2mm] \dfrac{2}{2+z} & \dfrac{z}{2+z} \end{bmatrix} \qquad (4.21)$$

where

$$z = \frac{Z}{Z_0},$$

and Z_0 is the characteristic impedance (50 Ohm) of the connected line. In this case, the TOUCHSTONE CAD program is useful in calculating the scattering parameters.

These theoretical outputs are shown in Appendix C. Also the magnitude plots of the calculated scattering parameters of this device are shown in Fig. 15.

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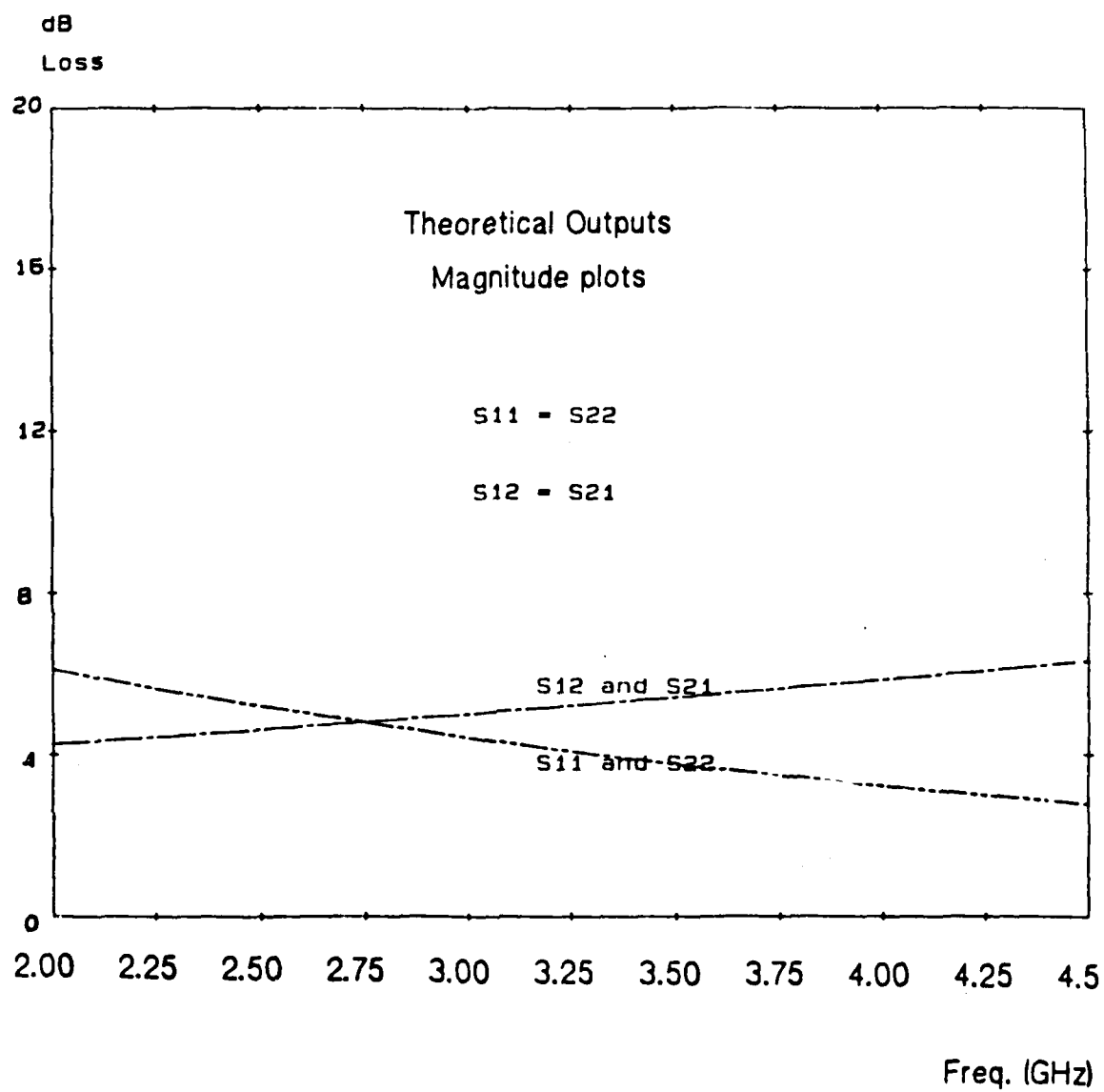
Figure 15. Theoretical Scattering Parameters of 51 Ohm Resistor

2. Device Embedment

The S-parameters of both fixtures plus device are measured by the network analyzer at planes AA′ and BB′ as shown in Fig. 16. Typical measured magnitude data is shown in Fig. 17 with data tables in Appendix C.
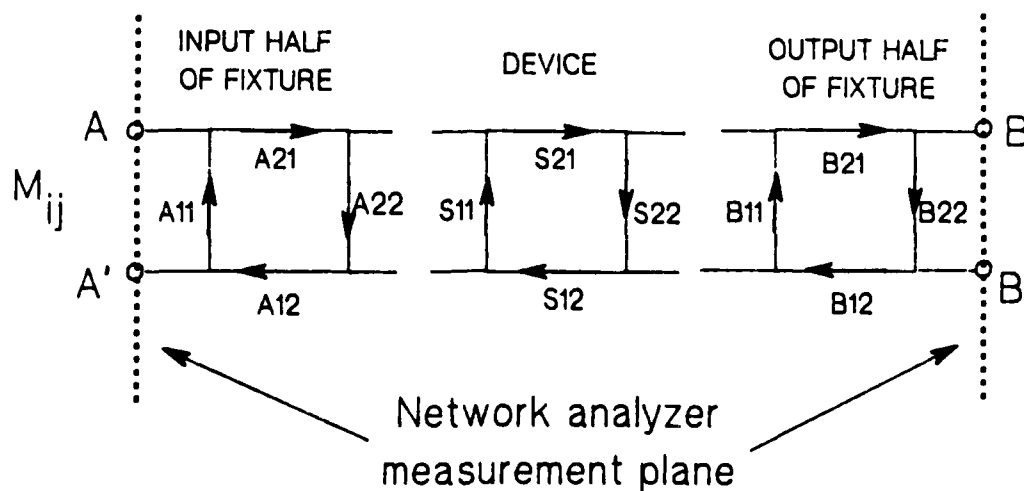
Figure 16. Signal Flow graph for the Measurement of the (Fixture + Device) S-parameters

30

dB
Loss

Fixtures + 51 Ohm Resistor Outputs
Magnitude plots

S11

S12

S21

S22

Freq. (GHz)
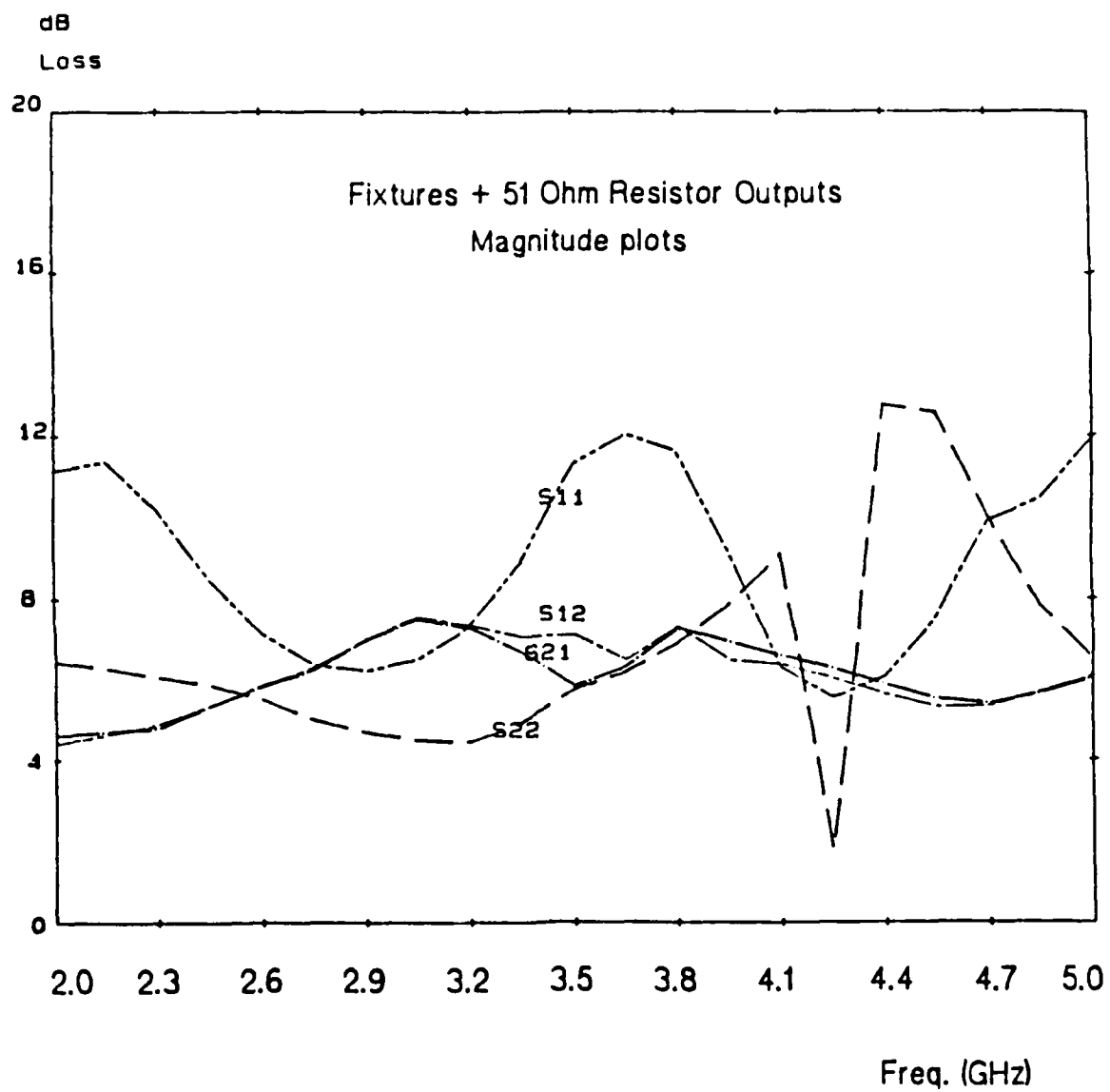
Figure 17.   The Magnitude Plot of Both Microstrip Fixture and 51 Ohm Resistor

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3. De-embedding the Device

Now we are ready for calculation of the S-parameters of the device. The S-parameters of fixture A, fixture B and both fixtures plus device constitute the necessary data. Once the microstrip circuit board is prepared, then the network analyzer provides the three different input reflection coefficients Γ_{in1}, Γ_{in2} and Γ_{in3} with respect to three different calibration loads. Also computations are carried out to find the load reflection coefficients of these three different loads, Γ_{L1}, Γ_{L2} and Γ_{L3}. After following the same procedure for both fixture A and fixture B, we can get the respective S-parameters. From the matrix equation (Eq. 2.17), the three unknowns S_{11}, S_{22} and Δ are solved. For de-embedding the device itself, we need the additional S-parameters for the device plus fixture. These three sets of S-parameters are utilized to solve the de-embedding problem.

Equations 4.11 to 4.14 are now ready for use. Through these equations, the de-embedded outputs are obtained, as shown in Fig. 18 (the table of de-embedded S-parameters is shown in Appendix C). In addition to the plot of the de-embedded magnitudes, the comparison of the scattering parameters S_{11}, S_{12} and S_{22} of the de-embedded output with the parameters of the embedded resistor and the theoretical values are also available in Fig. 19 to Fig. 21 (data tables in Appendix C).

dB

Loss

20

De-embedded Outputs

Magnitude plots

16

12

8

S12

S21

4

S22 S11

0

2.0   2.3   2.6   2.9   3.2   3.5   3.8   4.1   4.4   4.7   5.0

Freq. (GHz)
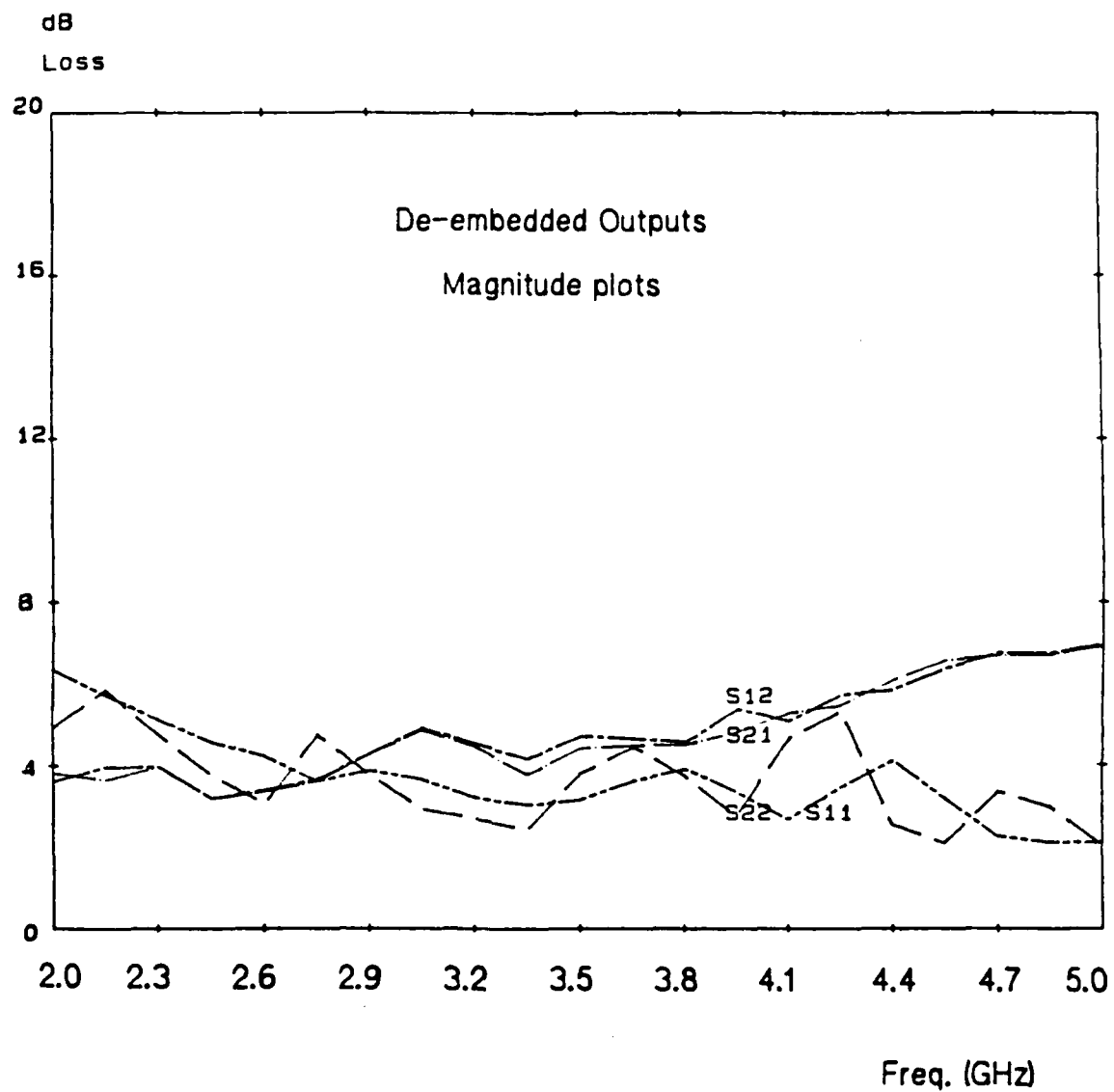
Figure 18.   Magnitude Plot of the De-embedded Parameters of 51 Ohm Resister
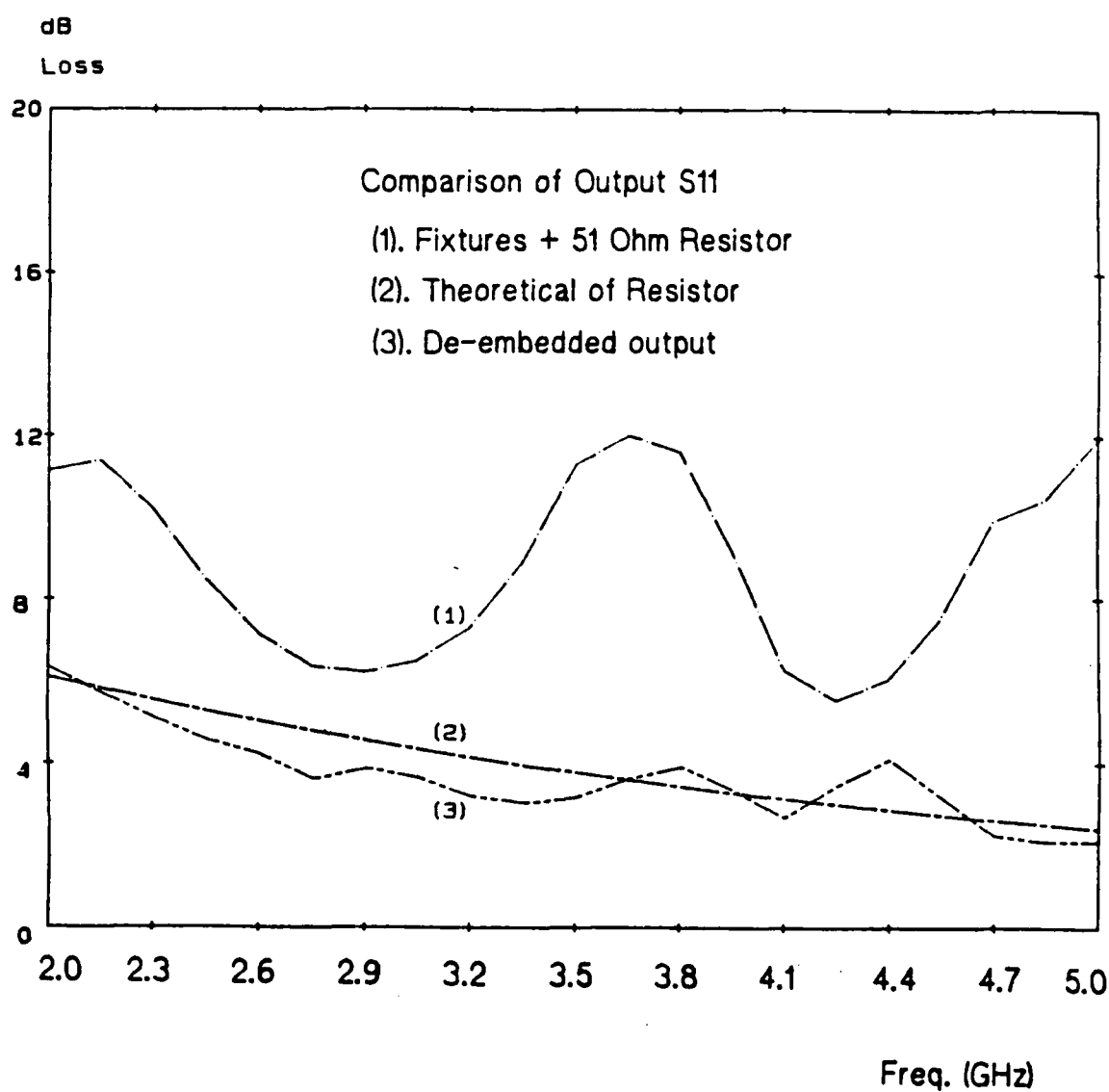
Figure 19.   Comparison of the S11 of the 51 Ohm Resistor with the Theoretical
            Values

34
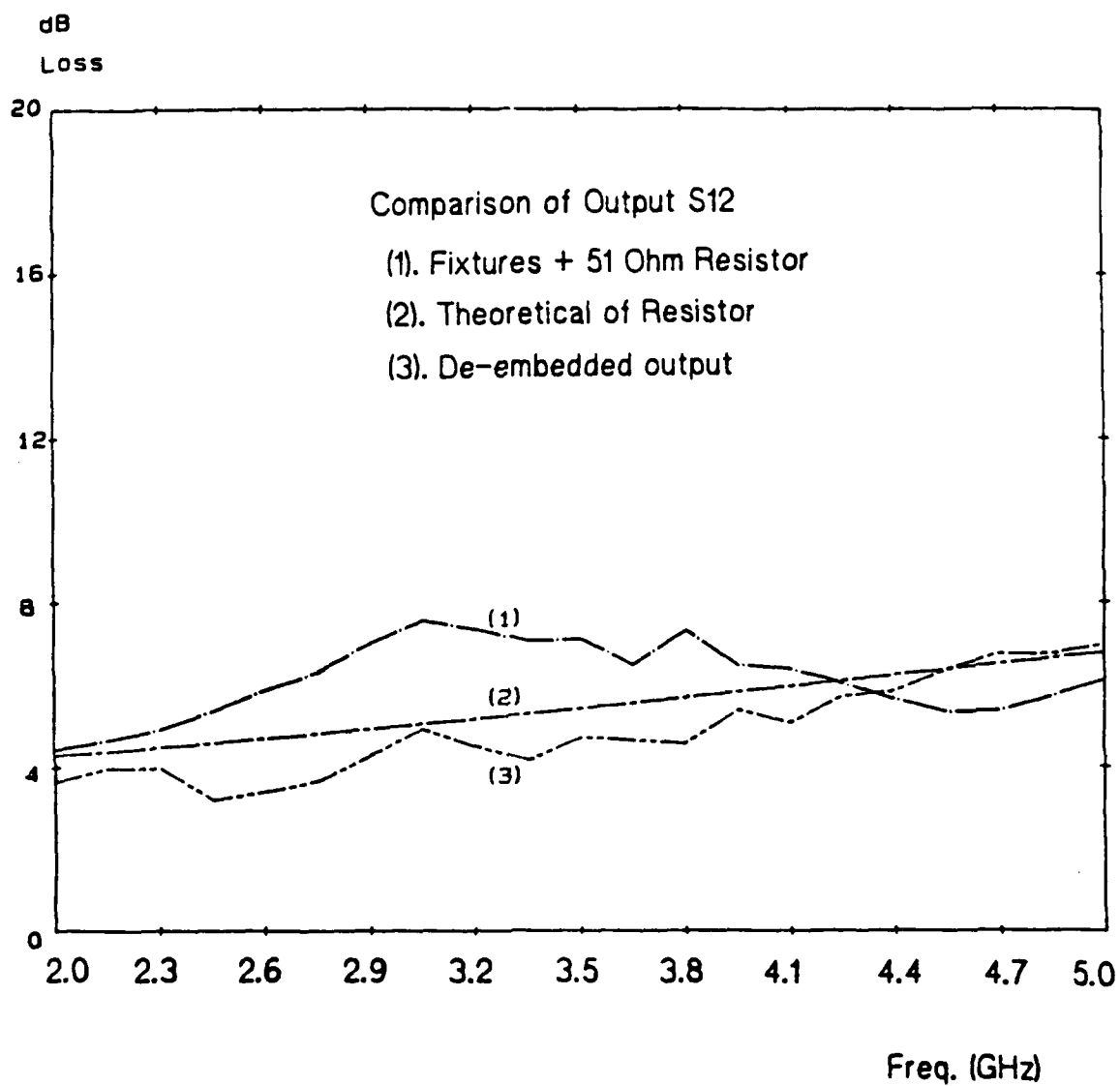
Figure 20. Comparison of the S12 of the 51 Ohm Resistor with the Theoretical
Values

dB
Loss

Comparison of Output S22

(1). Fixtures + 51 Ohm Resistor

(2). Theoretical of Resistor

(3). De-embedded output

Freq. (GHz)
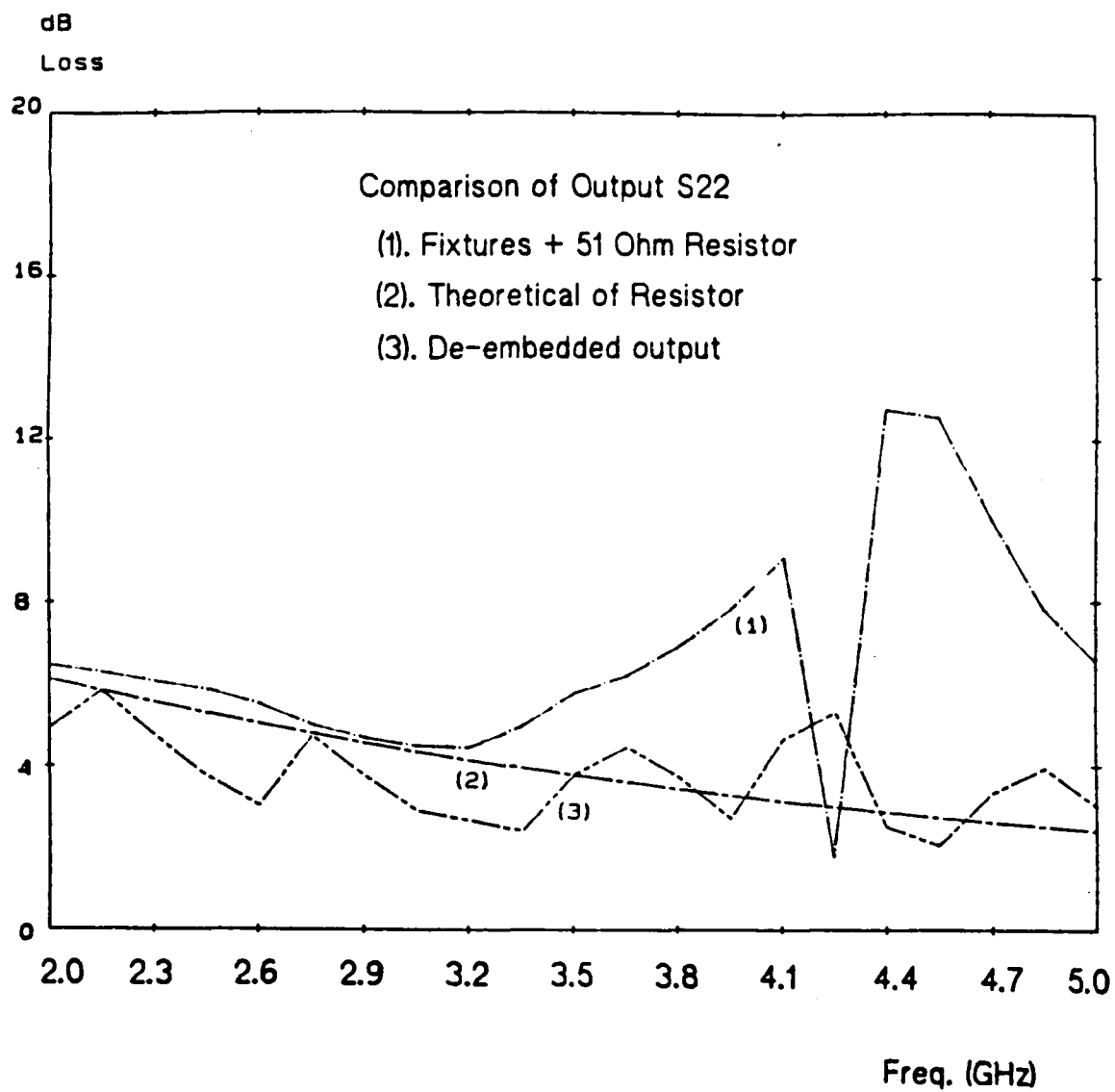
Figure 21. **Comparison of the S22 of the 51 Ohm Resistor with the Theoretical Values**

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V. FURTHER DE - EMBEDDING METHODS

A. MEASUREMENT OF DEVICE PARAMETERS USING A SYMMETRIC FIXTURE.

1. Background

As discussed earlier, if the device is constructed without a coaxial or waveguide interface, de-embedding becomes more difficult. In some cases, it is possible to proceed using an auxiliary standard whose properties are calculated or measured at low frequencies, but, in other cases, no suitable auxiliary standard is available. In either case, if the fixture is symmetric, a de-embedding procedure that does not require the use of an auxiliary standard can be developed [Ref. 5].

The concept for symmetric de-embedding is illustrated in Fig. 22. Fig. 22-a shows a device inserted in a symmetric test fixture. We assume that the device has complementary interfaces on the input and output sides so that when the device is removed from the fixture, the two halves of the fixture can be connected, as shown in Fig. 22-b. The scattering parameters of each half of the test fixture can be extracted from the scattering parameters of the whole test fixture connected, as illustrated in Fig. 22-b. Then the device is inserted into the test fixture, as illustrated in Fig. 22-a, and the scattering parameters are again measured.

The method for implementing the concept outlined above is as follows. If we have a fixture whose T-parameters in a 50 ohm system are $[TF]$, then if $[HTF]$ represents the square root of $[TF]$,

$$[HTF][HTF] = [TF]. \tag{5.1}$$

Now suppose we want to measure the T-parameters of a device in a 50 ohm system $[TS]$. If we separate the fixture into two symmetric parts and inserted the device to be measured, then for the combination we would measure a set of T-parameters $[TFS]$ given by:

$$[TFS] = [HTF][TS][HTF]. \tag{5.2}$$

To find $[TS]$, we would simply invert above equation to get

$$[TS] = [HTF]^{-1}[TFS][HTF]^{-1}. \tag{5.3}$$

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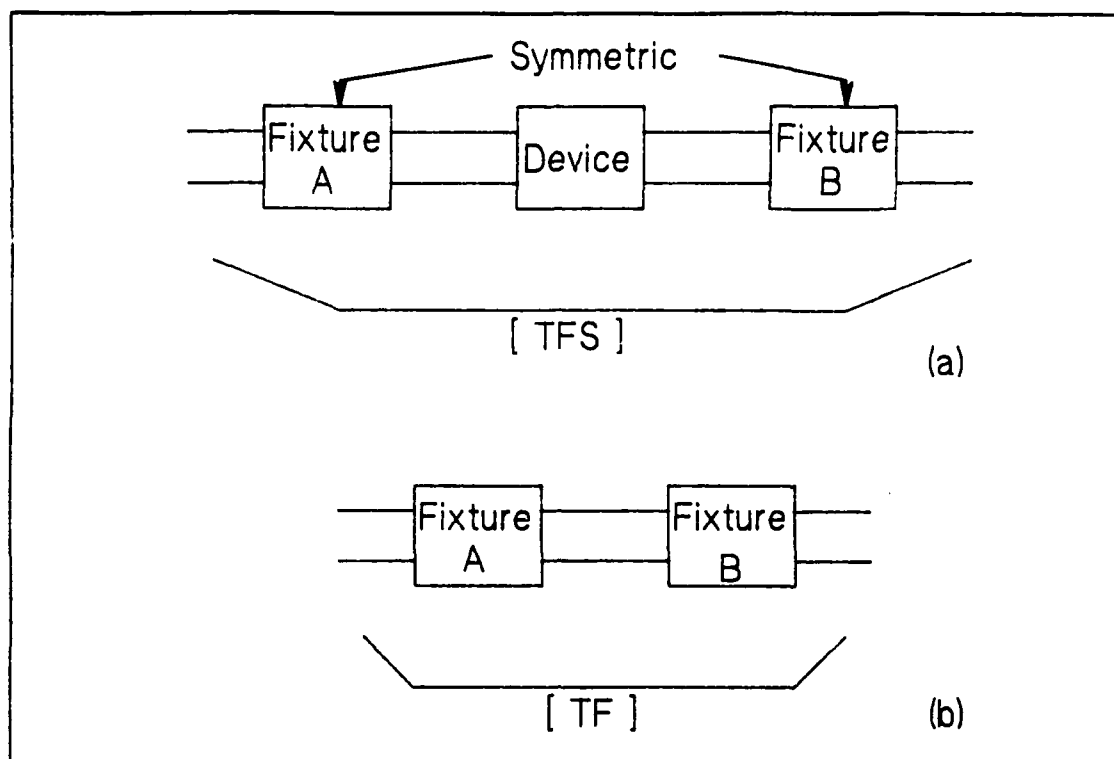
Figure 22. Device Embedded Between Symmetric Fixture and Test Fixture

This procedure de-embeds the device parameters $[TS]$ from the measured parameters $[TFS]$ and $[TF]$. The steps required to find $[TS]$ in a symmetric fixture are as follows:

1. Measure the scattering parameters of both fixture plus device, $[SFS]$, using the network analyzer,

$$[SFS] = \begin{bmatrix} SFS_{11} & SFS_{12} \\ SFS_{21} & SFS_{22} \end{bmatrix}$$

(5.4)

then transform to the T-parameters:

$$[TFS] = \begin{bmatrix} \dfrac{-M_1}{SFS_{21}} & \dfrac{SFS_{11}}{SFS_{21}} \\ \dfrac{-SFS_{22}}{SFS_{21}} & \dfrac{1}{SFS_{21}} \end{bmatrix}$$

(5.5)

where $M_1 = SFS_{11}SFS_{22} + SFS_{12}SFS_{21}$.

2. Measure the scattering parameters of both fixtures $[SF]$. In practice, both fixtures are measured with the network analyzer individually:

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$$[HSF] = [HSF1] = [HSF2] = \begin{bmatrix} HSF_{11} & HSF_{12} \\ HSF_{21} & HSF_{22} \end{bmatrix} \tag{5.6}$$

Then, transforming to the T-parameters:

$$[HTF] = \begin{bmatrix} \dfrac{-M_2}{HSF_{21}} & \dfrac{HSF_{11}}{HSF_{21}} \\ \dfrac{-HSF_{22}}{HSF_{21}} & \dfrac{1}{HSF_{21}} \end{bmatrix} \tag{5.7}$$

where $M_2 = HSF_{11}HSF_{22} + HSF_{12}HSF_{21}$.

3. Invert $[HTF]$:

$$[HTF]^{-1} = \begin{bmatrix} \dfrac{HTF_{22}}{M_3} & \dfrac{-HTF_{21}}{M_3} \\ \dfrac{-HTF_{12}}{M_3} & \dfrac{HTF_{11}}{M_3} \end{bmatrix} \tag{5.8}$$

where $M_3 = HTF_{11}HTF_{22} - HTF_{21}HTF_{12}$.

4. Find device T-parameters $[TS]$:

$$[TS] = \begin{bmatrix} HTF_{11} & HTF_{12} \\ HTF_{21} & HTF_{22} \end{bmatrix}^{-1} \begin{bmatrix} TFS_{11} & TFS_{12} \\ TFS_{21} & TFS_{22} \end{bmatrix} \begin{bmatrix} HTF_{11} & HTF_{12} \\ HTF_{21} & HTF_{22} \end{bmatrix}^{-1} \tag{5.9}$$

5. Transform $[TS]$ to S-parameters $[SS]$:

$$[SS] = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}$$

where

$$S_{11} = \frac{TS_{12}}{TS_{22}} \tag{5.10}$$

$$S_{12} = TS_{11} - \frac{TS_{12}TS_{21}}{TS_{22}} \tag{5.11}$$

$$S_{21} = \frac{1}{TS_{22}} \tag{5.12}$$

$$S_{22} = -\frac{TS_{21}}{TS_{22}} \tag{5.13}$$

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2. De-Embedding of a Filter Unit

As a test demonstration of the symmetrical de-embedment procedure, an 8436A bandpass filter (8 - 12 GHz) is used as the test device. All components of the network had type APC-7 test port connectors. The outputs [SFS] and [HSF] of the network analyzer are shown in Appendix D. To get the de-embedded outputs, the Fortran program shown in Appendix F is used. The magnitude plot of the filter embedded, the filter itself, and the de-embedded filter are shown in Figs. 23 to 25. Data Tables are shown in Appendix D. The comparison of the scattering parameters S_{11}, S_{12} and S_{22} of the filter itself, and embedded filter are shown in Figs. 26 to 28. Tabulated data is shown in Appendix D.
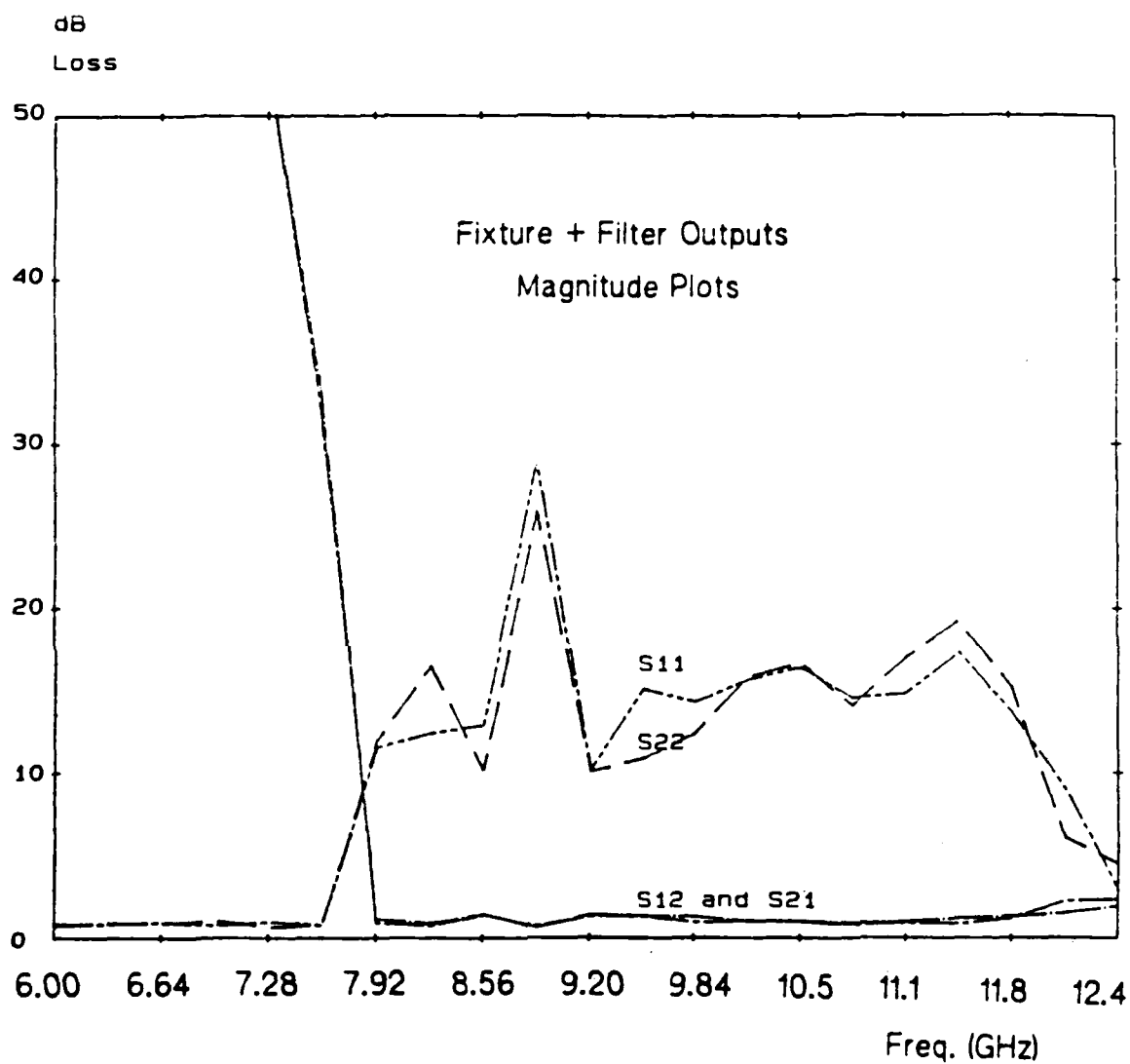
Figure 23.   The S-parameter Magnitude Plot of Both Fixture and Filter

41
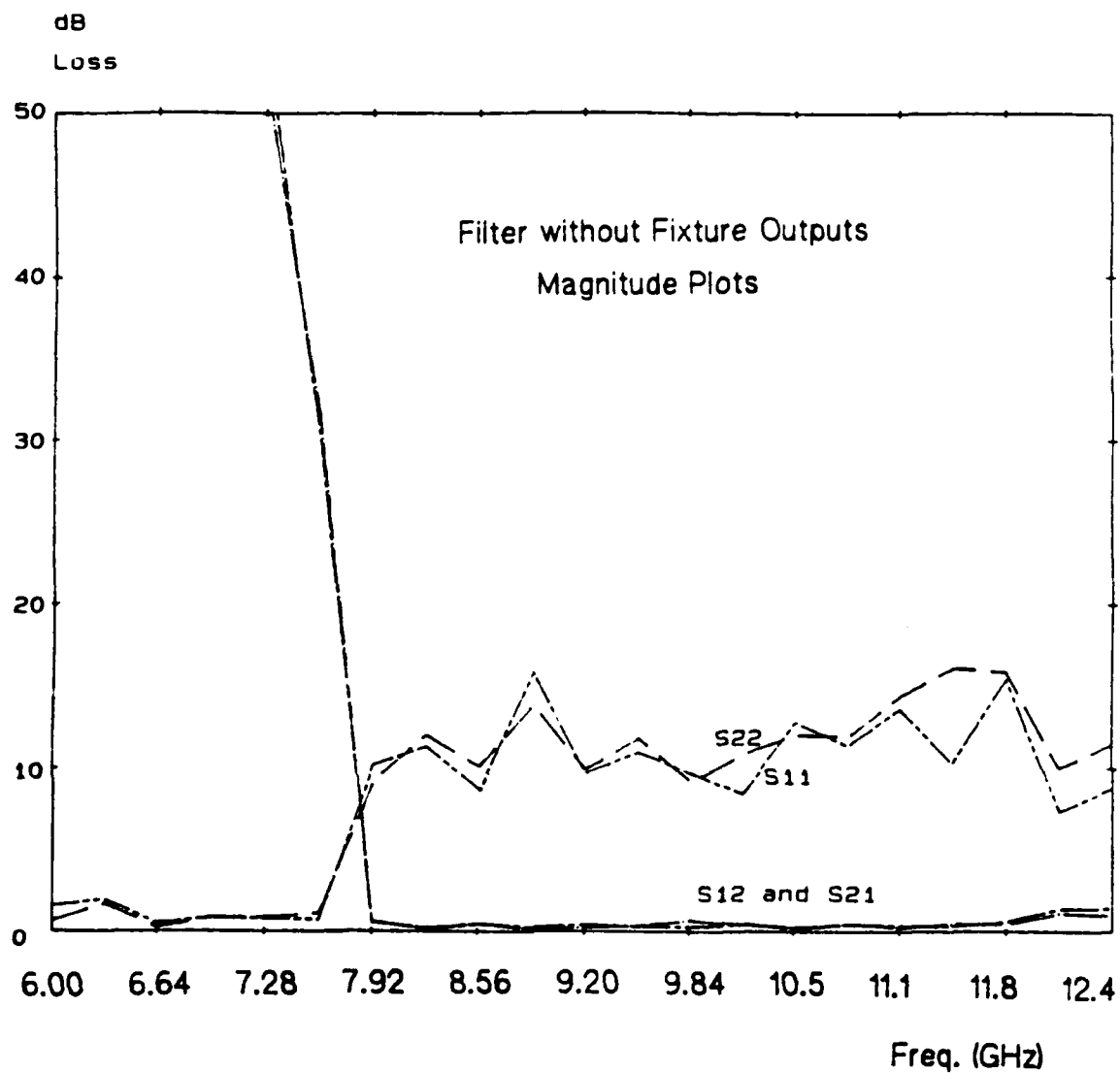
Figure 24.   The S-parameter Magnitude Plot of Filter Without Fixtures

42
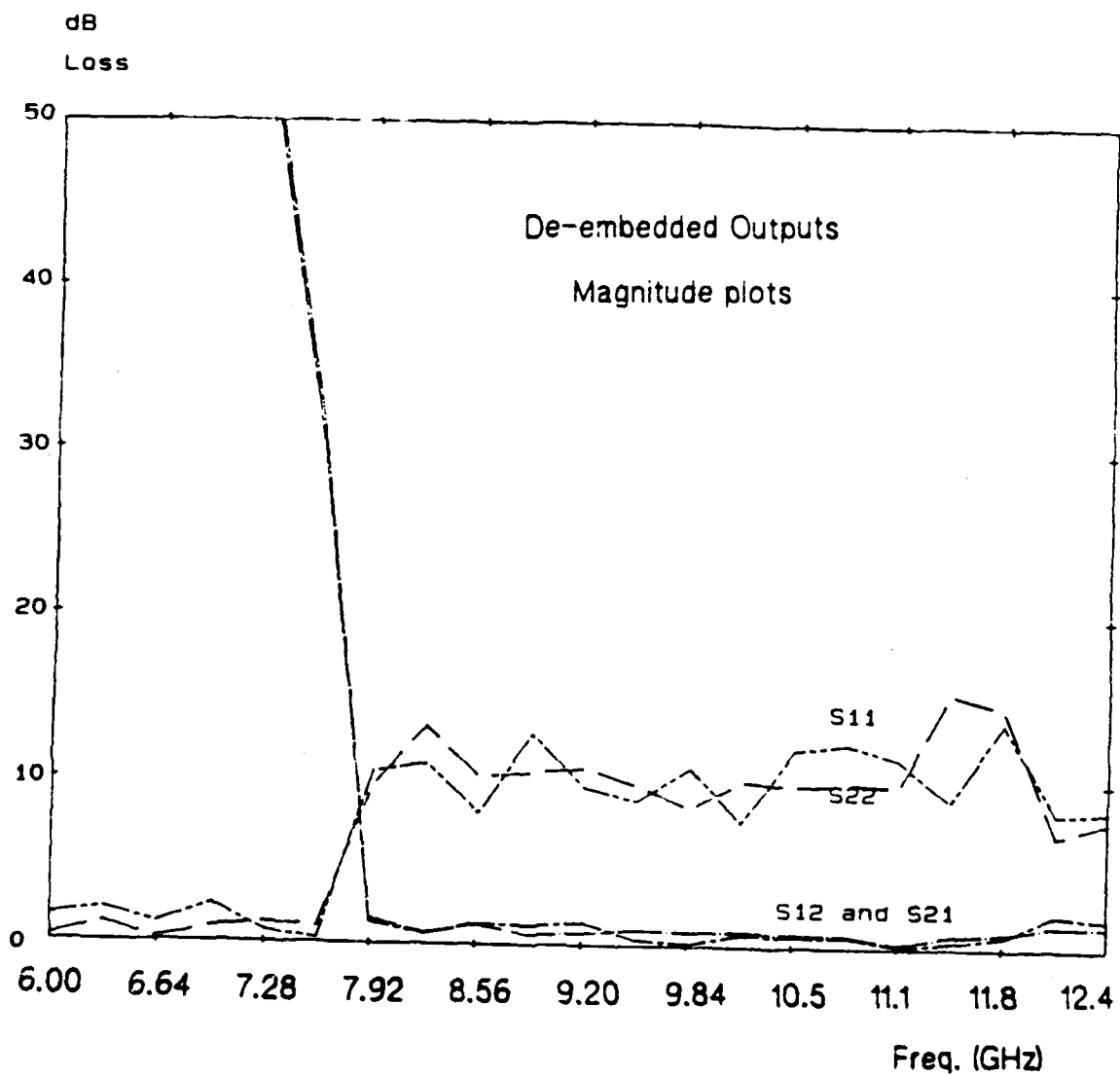
Figure 25.   The S-parameter Magnitude Plot of De-embedded Parameters of Filter

dB
Loss

Comparison of Output S11

(1). Fixtures + Filter

(2). Filter without Fixtures

(3). De-embedded output

Freq. (GHz)
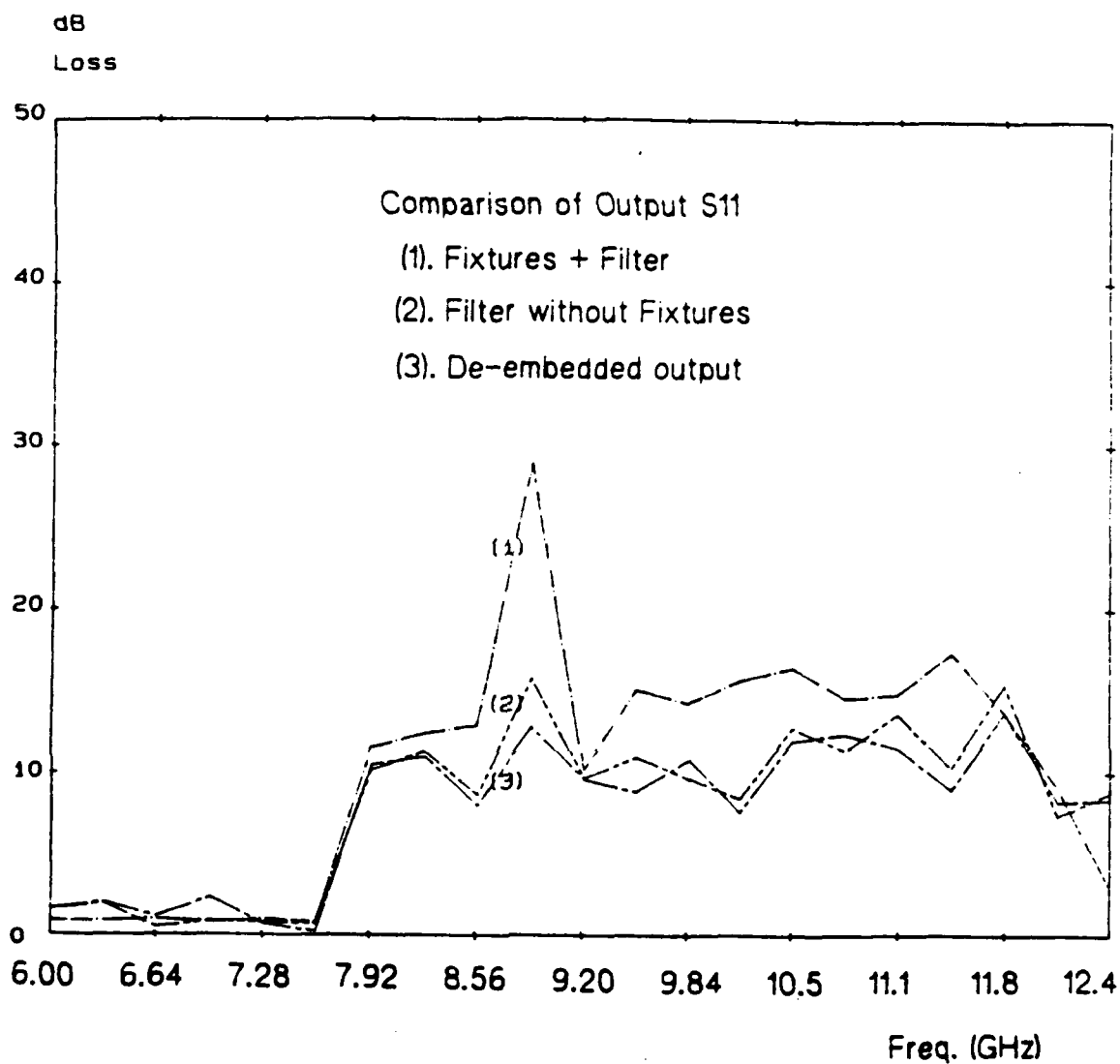
Figure 26.   Comparison of the S11 of De-embedded Filter with Filter Without Fixtures

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dB
Loss

Comparison of Output S12
(1). Fixtures + Filter
(2). Filter without Fixtures
(3). De-embedded output

Freq. (GHz)
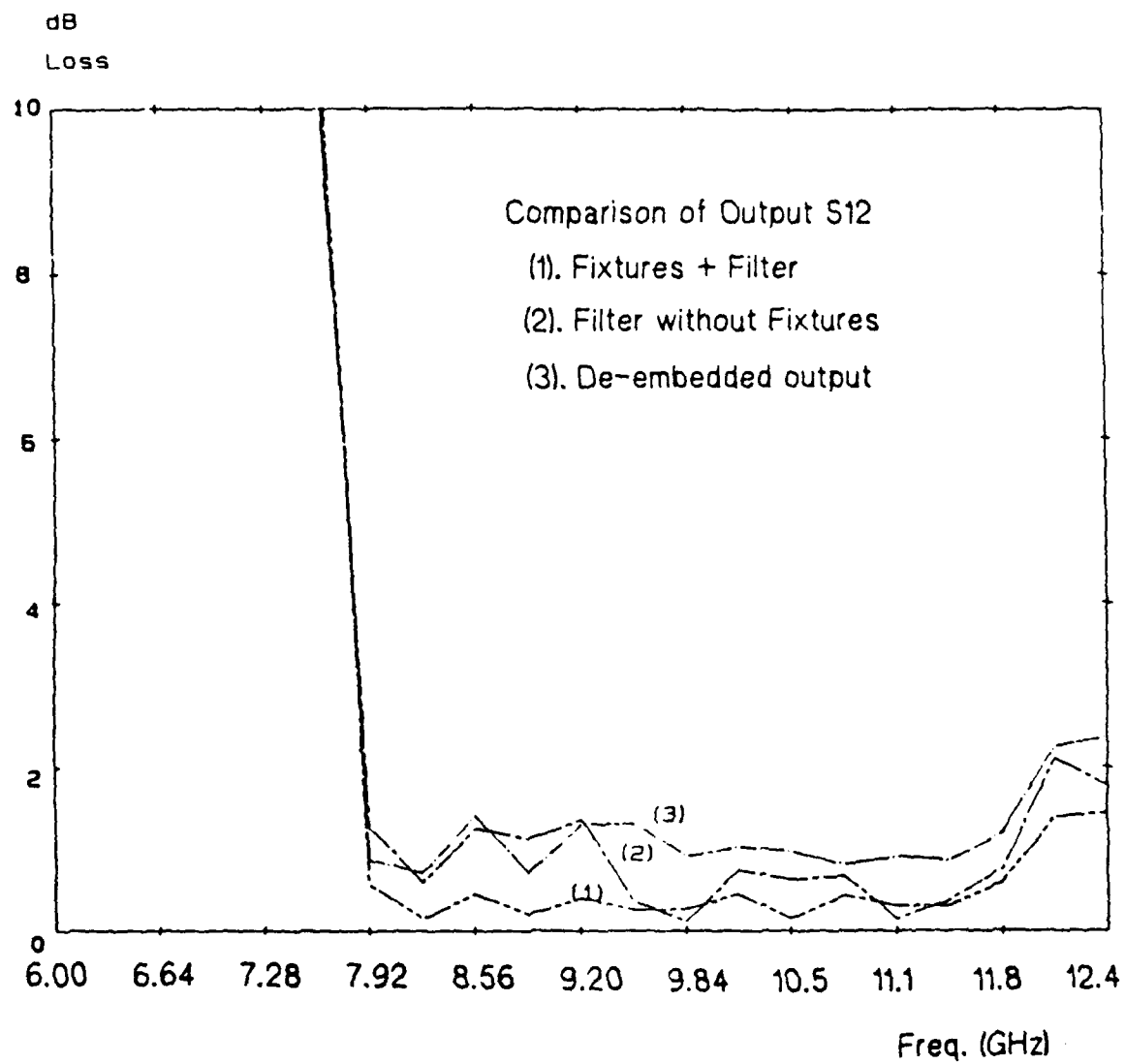
Figure 27.   Comparison of the S12 of De-embedded Filter with Filter Without Fixtures

45
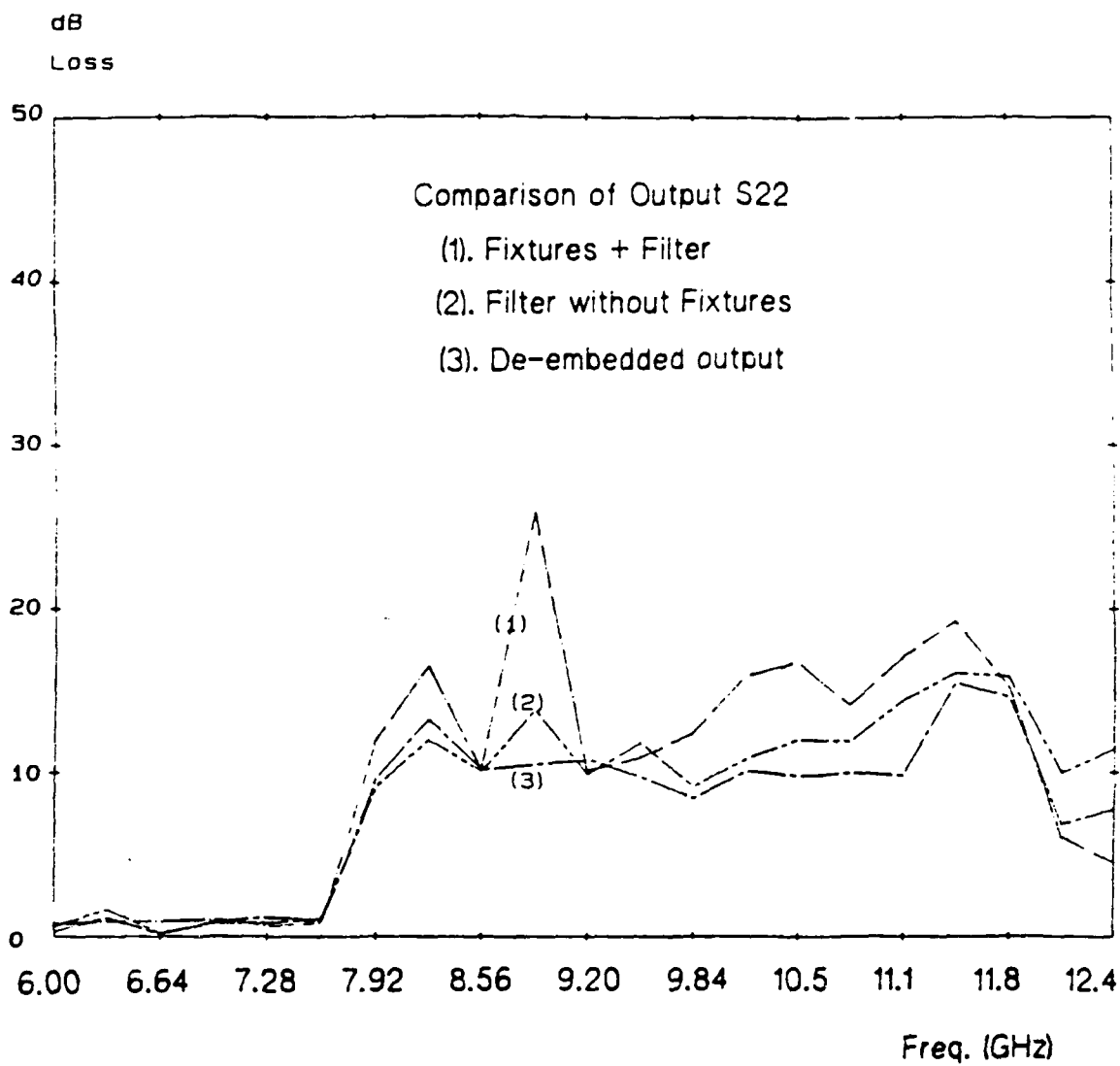
Figure 28.   Comparison of the S22 of De-embedded Filter with Filter Without Fixtures

B. TSD (THROUGH, SHORT, DELAY) METHOD

This procedure, developed by R. Speciale [Refs. 6, 7], is intended for system calibration and systematic error removal in automated S-parameter measurement. This procedure uses only three non-critical reference standards, called the "Through", the "Short" and the "Delay", and leads to a set of equations for which a fast, non-iterative, explicit solution is known [Ref. 6].

1. The Basic Concept

This procedure uses only three mechanically simple reference standards, known respectively as the "Through", the "Short", and the "Delay".

The "Through" is defined as the direct mutual connection of fixtures A and B, as shown in Fig. 29, when the uncalibrated S-parameter data for the device are acquired. The S-parameter data for "Through" are therefore acquired with the measurement lines to the device directly interconnected and the device removed from the signal path.

The "Short" is defined as a reference object presenting perfect shorts at the immediate interfaces where the unknown device is connected for measurement.

Finally, the "Delay" is defined as any arbitrary length of 50 ohm line inserted between the interfaces where the unknown device is connected for measurement. Summarizing, for the "Through" and the "Delay", the signal path is continuous between ports 1 and 2 of the S-parameter unit, through the couplers used for connecting the object. A direct connection represents the "Through" and a finite arbitrary length line for the "Delay", in place of the unknown object. On the contrary the signal path is blocked for the "Short" by perfect shorts appearing at the interfaces where the unknown device is normally connected.

Three S-parameter matrices $[S_T]$, $[S_S]$ and $[S_D]$ are acquired at each desired frequency during system calibration. These matrices describe the "Through", the "Short" and the "Delay" respectively. Because of the device imperfections, these matrices do not represent theoretically perfect "Through", "Short" and "Delay" elements, which are assumed to exist in the actual measurement.

Now consider the error boxes A and B. Error box A is assumed to be connected on the side of port 1, while error box B is assumed to be on the side of port 2, as shown in Fig. 29.

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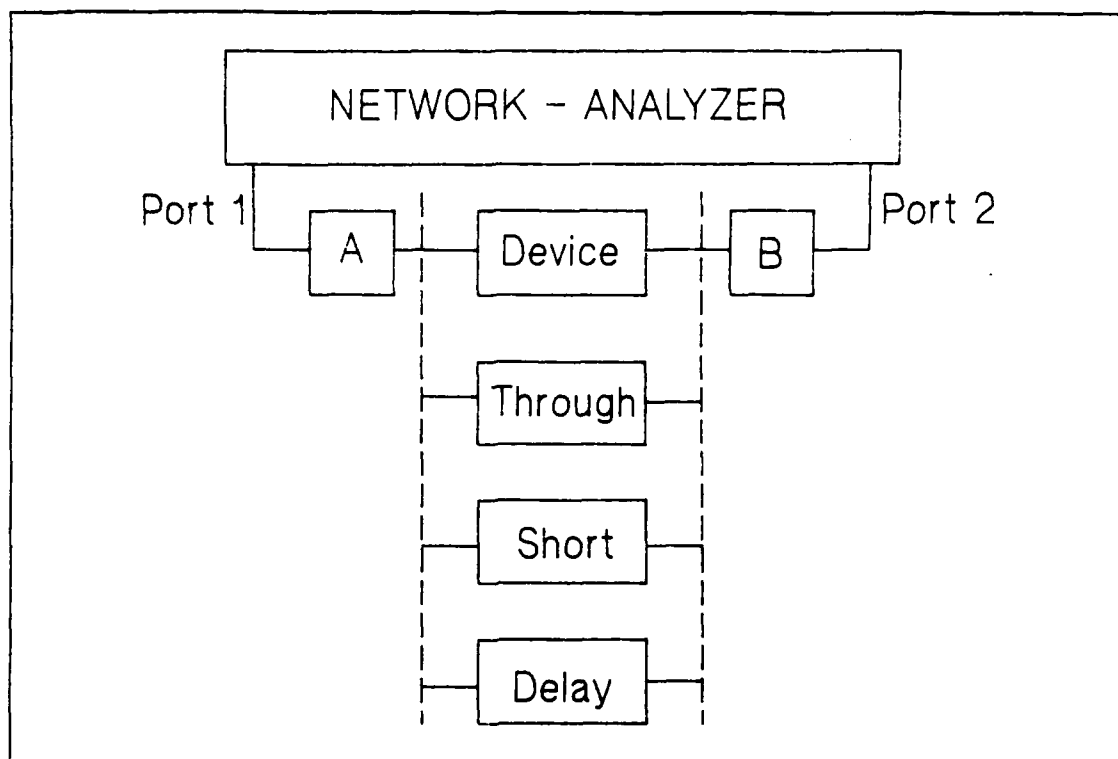
Figure 29. Block Diagram of the TSD Calibration Procedure

From Fig. 29, the error boxes A and B are always assumed to be inserted at the two ends of the measurement 50 ohm lines connecting the device to ports 1 and 2 of the S-parameter unit. An algorithm has been derived wh·,h performs an explicit, non-iterative calculation of the S-parameter matrices $[S_A]$ and $[S_B]$, which characterize the virtual error boxes A and B.

2. The Equations and their Explicit solution

As discussed earlier, the T-matrices can be multiplied simply with cascaded elements. Therefore, consider Fig. 30, where the T-matrix for the connection shown is:

$$[T_{ADB}] = [T_A] \ [T_D] \ [T_B].$$ (5.14)

From the above, we get:

$$[T_D] = [T_A]^{-1} \ [T_{ADB}] \ [T_B]^{-1}$$ (5.15)
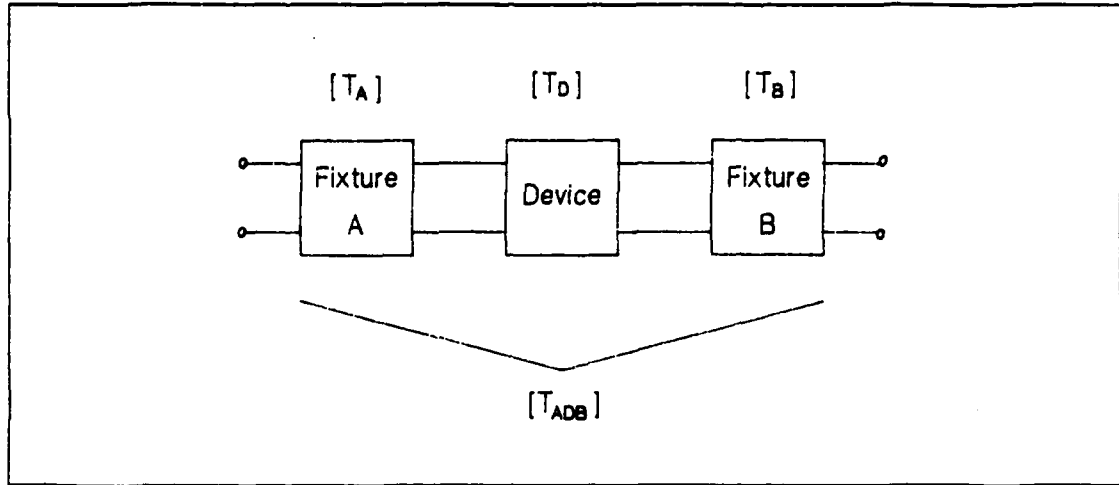
Figure 30.   Device Embedded Setup

where $[T_D]$ is the corrected T-matrix and $[T_{ADB}]$ is the uncalibrated T-matrix for the device.

The T-parameters of fixtures plus device, $[T_{ADB}]$, are given by the network analyzer. But the problem is to obtain the T-parameters of each fixture, $[T_A]$ and $[T_B]$. To do this, we consider the error boxes A and B as shown in Fig. 31.

From a formal point of view, both the "Through" and the "Delay" can be considered as different, finite lengths of 50 ohm lines, cascaded between the error boxes A and B. With $[T_{D1}]$ and $[T_{D2}]$, the T-matrix derived from the S-parameter data obtained in these two calibrations, and $[T_A]$ and $[T_B]$, the unknown T-parameters of the error boxes A and B, we can write:

$$[T_{D1}] = [T_A][T_{L1}][T_B],$$
(5.16)

$$[T_{D2}] = [T_A][T_{L2}][T_B].$$
(5.17)

For the 50 ohm lines L_1 and L_2 we have:

$$[T_{L1}] = \begin{bmatrix} e^{-\rho_1} & 0 \\ 0 & e^{\rho_1} \end{bmatrix}$$
(5.18)

where $\rho_1 = r_1 + j\theta_1$.

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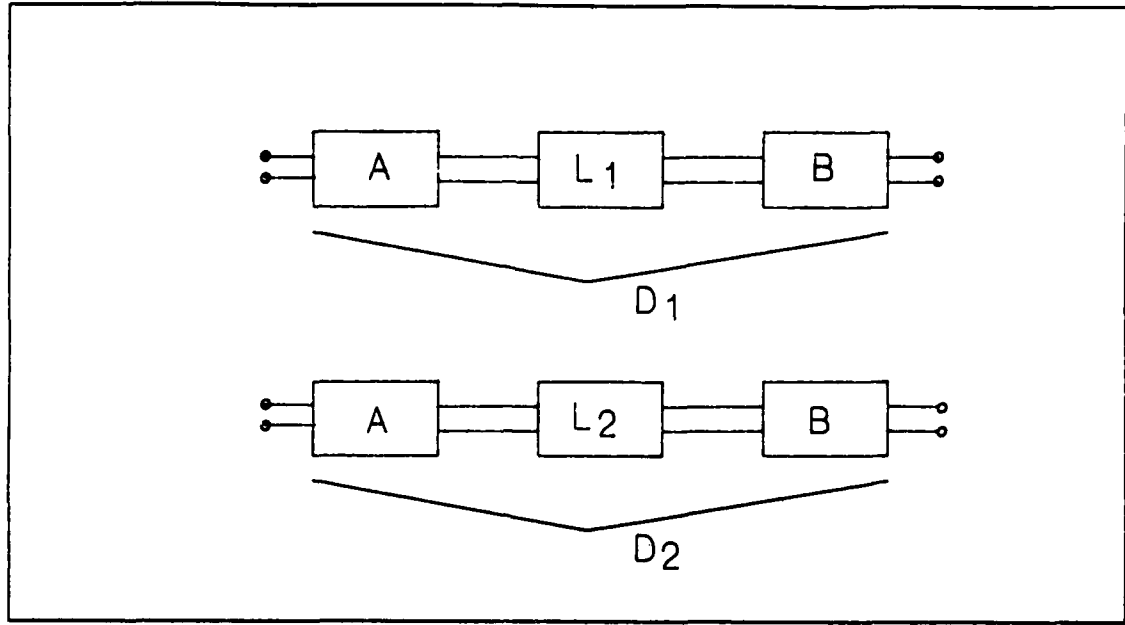
Figure 31.   Error Boxes of A and B with Delay

$$[T_{L2}] = \begin{bmatrix} e^{-\rho_2} & 0 \\ 0 & e^{\rho_2} \end{bmatrix}$$

(5.19)

where $\rho_2 = r_2 + j\theta_2$.

Equations (5.16) and (5.17) together with the two equations for the "Short" characterize boxes A and B. Also, consider the situation for the "Short", as shown in Fig. 32, we have

$$S_{11S} = \frac{b_{1A}}{a_{1A}} = \frac{S_{11A} + \det S_A}{1 + S_{22A}}$$

(5.20)

$$S_{11S} = \frac{b_{2B}}{a_{2B}} = \frac{S_{22B} + \det S_B}{1 + S_{11B}}$$

(5.21)

where S_{11S} and S_{22S} are S_{11} and S_{22} of the "Short", and S_{iiA}, S_{iiB} are S_{ii} of box A and box B (det means matrix determinant), where i= 1, 2.

From Eqs. (5.16) and (5.17), we get:

$$S_{11A} = \frac{T_{12A}}{T_{22A}} = \frac{H_3}{H_1}$$

(5.22)

50
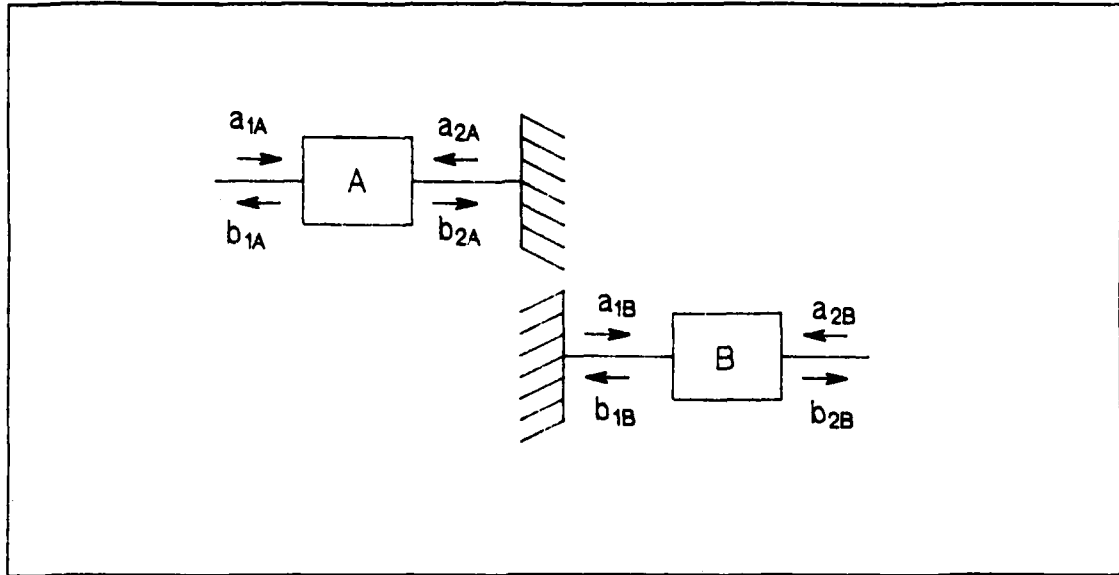
Figure 32. Short Situation of Two Error Boxes

$$\det S_A = S_{22A} \; \frac{H_1}{H_4} \tag{5.22a}$$

$$S_{22B} = \frac{-T_{21B}}{T_{22B}} = \frac{-K_4}{K_1} \tag{5.23}$$

$$\det S_B = S_{11B} \; \frac{-K_1}{K_3} \tag{5.23a}$$

Now substitute Eqs. (5.22) and (5.22a) into (5.20) to obtain:

$$S_{22A} = \frac{\dfrac{H_3}{H_1} - S_{11S}}{S_{11S} - \dfrac{H_1}{H_4}} \tag{5.24}$$

and also,

$$S_{12A}S_{21A} = S_{11A}S_{22A} - \det S_A$$

$$= \left[S_{11A} - \frac{H_1}{H_4} \right] S_{22A} \tag{5.25}$$

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Substituting Eqs. (5.23) and (5.23a) into (5.21),

$$S_{11B} = \frac{\dfrac{K_4}{K_1} - S_{22S}}{S_{22S} + \dfrac{K_1}{K_3}}$$

(5.26)

$$S_{12B}S_{21B} = S_{11B}S_{22B} - \det S_B$$

$$= \left[S_{22B} + \frac{K_1}{K_3} \right] S_{11B}$$

(5.27)

where

$$H_1 = \frac{1}{2}\left[1 + \frac{H_{22} - H_{11}}{2\sinh\rho} \right]$$

(5.28)

$$K_1 = \frac{1}{2}\left[1 + \frac{K_{22} - K_{11}}{2\sinh\rho} \right]$$

(5.29)

$$H_3 = \frac{H_{12}}{2\sinh\rho}$$

(5.30)

$$K_3 = -\frac{K_{12}}{2\sinh\rho}$$

(5.31)

$$H_4 = -\frac{H_{21}}{2\sinh\rho}$$

(5.32)

$$K_4 = \frac{K_{21}}{2\sinh\rho}$$

(5.33)

Here the quantities H_{ij} and K_{ij} are the elements of the matrices $[H]$ and $[K]$, defined by

$$[H] = [T_{D1}]\,[T_{D2}]^{-1}$$

(5.34)

$$[K] = [T_{D2}]^{-1}\,[T_{D1}]$$

(5.35)

and ρ is defined by:

$$\rho = \cosh^{-1}\left[\frac{1}{2}(H_{11} + H_{22})\right] = \cosh^{-1}\left[\frac{1}{2}(K_{11} + K_{22})\right] \tag{5.36}$$

Once the S-parameters of the error boxes A and B are known as given by Eqs. (5.22) through (5.27), use the general conversion formulas,

$$[T] = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \frac{1}{S_{21}}\begin{bmatrix} -\det S & S_{11} \\ S_{22} & 1 \end{bmatrix} \tag{5.37}$$

where $\det S = S_{11}S_{22} - S_{12}S_{21}$.

As discussed before, the following calculation to de-embed the device matrix,

$$[T_D] = [T_A]^{-1} \ [T_{ADB}] \ [T_B]^{-1},$$

can be carried out using Eqs. (5.22) through (5.27).

3. Discussion

This calibration procedure uses only three reference standards, which is the minimum necessary for characterizing the error boxes A and B. By using two delays of different length, for a total of 4 standards, a check of intrinsic consistency may be obtained. The standards used are simple enough to be inserted at the location of the object, even if this is an active device contained in some kind of measurement fixture. In this way, all system errors are removed, including those introduced by the fixture.

The position of the reference plane is immaterial, as long as it is kept constant during calibration and measurement. Also, the given solution of the relevant network equations is an exact, explicit solution. Finally, the procedure is essentially independent of the specific system configuration.

VI. CONCLUSION

Various sources have been cited for the extraction of the scattering parameters of a device by removal of the error and contributions of the fixturing setup [Refs. 8,9,10,11]. In Chapters II and III, the de-embedding procedure using microstrip line within the given conditions was discussed. This project included various aspects such as the microstrip line fixturing setup and the construction and handling of small experimental boards. But in spite of the limitations of the early-model Network analyzer HP 8409B which was available for this work, the best possible results were obtained using repeated measurements on the same experimental board to obtain mean values.

To extract the scattering parameters of the device 51 ohm resistor, the nine basic parameters as discussed earlier in Chapter IV (Eqs. 4-11 to 4-19) were used. These equations required the scattering parameters of both fixtures since they are not symmetrical. That is, individual measurements and calculations were required for both fixtures. The matrix equation (Eq. 2-17) involved the three unknown scattering parameters S_{11}, S_{22} and $\Delta \equiv (S_{11}S_{22} - S_{12}S_{21})$ for fixture A and B. That meant each fixture required three equations for the matrix solution. Three different measurements and calculations of microstrip line were used to set up the above matrix entries, i.e, three different measured reflection coefficients from the network analyzer with respect to the three different microstrip loads, respectively Γ_{in1}, Γ_{in2} and Γ_{in3} and three different calculated reflection coefficients at the terminals of the three different loads Γ_{L1}, Γ_{L2} and Γ_{L3} were required. The computed value for S_{11} and S_{22} are combined with a knowledge of Δ which can be used to determine the $S_{12}S_{21}$ product. Since S_{12}, and S_{21} for the fixtures always appear in product form, the magnitude of these terms can be calculated as the square root of the product term in the expression for Δ .

The de-embedded scattering parameters of the device (51 ohm resistor) were found through experiment to be close to the theoretically calculated values, shown in magnitude plots in Figs. 19, 20, and 21 and as tabulated in Table 4. As may be seen in Figs. 19 to 21, the theoretically calculated scattering coefficients of the 51-Ohm resistor device showed only a slight continuous variation over the entire frequency range of interest. The measured values of the embedded device showed, however, rapid irregular fluctuations with frequency, reflecting the probable occurrence of internal resonances within

parasitic discontinuities of the coupling circuitry. It is the task of the de-embedding procedure to remove these effects from the measurement. The curves numbered (3) in the above Figures show the de-embedded measurements, in comparison with the theoretical curves. As may be seen, the de-embedded results followed the expected values closely, showing fluctuations which are assumed to be due to measurement error, and network-analyzer calibration errors.

Table 4. THE COMPARISON OF THE OUTPUT FOR THE 51 OHM RESISTOR IN DB UNITS

Freq.(MHz)	Theoretical	De-embedded	Embedded
2000.0	6.11	6.35	11.14
2300.0	5.54	5.12	10.18
2600.0	5.02	4.22	7.13
2900.0	4.55	3.87	6.21
3200.0	4.13	3.19	7.33
3500.0	3.76	3.16	11.29
3800.0	3.42	3.91	11.59
4100.0	3.12	2.66	6.27
4400.0	2.86	4.11	6.07
4700.0	2.62	2.25	9.91
5000.0	2.41	2.11	11.95

S_{12} and S_{21} terms for fixture A and B always appears in product form, considering their phase is not important. As long as the phase angles of S_{21} for fixture A and S_{21} for fixture B are approximately the same, one can choose either of the phase angles. Some confusion may arise, if the scattering parameters of both fixture A and B are specified independently of the final device (51 ohm resistor) parameters. In this case, the approximate phase shift through one fixture can be computed, or determined exper-

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imentally, and used to choose the proper phase of S_{21} for fixture A and S_{21} for fixture B.

In Chapter V, the de-embedding procedure with symmetrical fixtures was carried out, using as the device a commercial bandpass filter (8-12 GHz). Standard hardware couplers were added to represent the fixtures. Since the fixtures were symmetrical, the de-embedding procedure was relatively straightforward. As may be seen in Figs. 26 to 28, the de-embedded scattering parameters of the filter were very close to the expectation values, i.e. of the scattering parameters of filter without fixtures. It may also be noted that the measured S-parameters of the embedded filter (fixtures plus filter) were very similar to those of the filter alone, except of course for phase; indicative of well-matched coupling hardware. Therefore, in this task, the de-embedded results were found to be in good agreement with the expected values, as shown in Figs. 26 through 28.

APPENDIX A.   THE OUTPUTS OF THE NETWORK ANALYZER AND THEIR REFLECTION COEFFICIENTS FOR FIXTURE A AND B
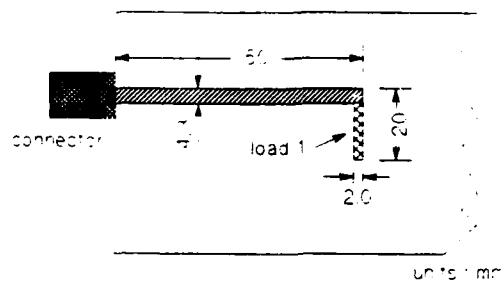
Figure 33.   Measurement of the Load 1 (Fixture A)

Table 5.   THE MEASUREMENT OF THE LOAD 1(FIXTURE A)

Freq.(MHz)	dB (loss)	Angle(deg.)	Γ_m
2000.0	3.07	22.7	0.65 + j0.27
2150.0	3.82	-63.1	0.29 - j0.57
2300.0	3.79	-153.9	-0.58 - j0.28
2450.0	3.46	126.4	-0.40 + j0.54
2600.0	3.20	60.5	0.34 + j0.60
2750.0	3.33	-1.7	0.68 - j0.02
2900.0	4.04	-69.9	0.22 - j0.59
3050.0	5.39	-152.8	-0.48 - j0.25
3200.0	6.17	107.6	-0.15 + j0.47
3350.0	5.32	17.1	0.52 + j0.16
3500.0	4.65	-51.0	0.37 - j0.45
3650.0	3.97	-111.9	-0.24 - j0.59
3800.0	4.89	-175.9	-0.57 - j0.04
3950.0	7.73	104.5	-0.10 + j0.40
4100.0	7.36	-17.1	0.41 - j0.13
4250.0	6.70	-121.4	-0.24 - j0.39
4400.0	4.59	170.4	-0.58 + j0.10
4550.0	4.12	114.2	-0.26 + j0.57
4700.0	4.88	58.9	0.29 + j0.49
4850.0	7.91	-9.1	0.40 - j0.06
5000.0	8.42	-137.9	-0.28 - j0.25

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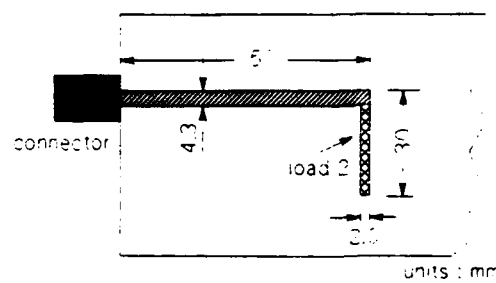
Figure 34.   Measurement of the Load 2 (Fixture A)

Table 6.   THE MEASUREMENT OF THE LOAD 2 (FIXTURE A)

Freq.(MHz)	dB (loss)	Angle(deg.)	Γ_{in}
2000.0	2.28	98.2	-0.11 + j0.76
2150.0	2.89	29.5	0.62 + j0.35
2300.0	3.77	-49.2	0.42 - j0.49
2450.0	4.12	-138.0	-0.46 - j0.42
2600.0	3.75	136.6	-0.47 + j0.45
2750.0	3.31	65.1	0.29 + j0.62
2900.0	3.40	4.9	0.67 + j0.06
3050.0	3.60	-54.2	0.39 - j0.54
3200.0	4.55	-119.0	-0.29 - j0.52
3350.0	5.78	159.8	-0.48 + j0.18
3500.0	6.39	61.8	0.23 + j0.42
3650.0	5.76	-25.5	0.47 - j0.22
3800.0	5.70	-89.0	0.01 - j0.52
3950.0	4.69	-134.2	-0.41 - j0.42
4100.0	3.91	173.7	-0.63 + j0.07
4250.0	4.48	117.4	-0.27 + j0.53
4400.0	6.84	47.9	0.31 + j0.34
4550.0	8.48	-61.4	0.18 - j0.33
4700.0	7.57	-174.8	-0.42 - j0.04
4850.0	4.92	115.1	-0.24 + j0.51
5000.0	3.99	62.0	0.30 + j0.56
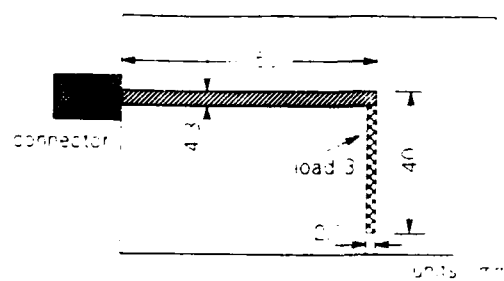
Figure 35.   Measurement of the Load 3 (Fixture A)

Table 7.   THE MEASUREMENT OF THE LOAD 3 (FIXTURE A)

Freq.(MHz)	dB (loss)	Angle(deg.)	$\Gamma_{..}$
2000.0	2.14	175.1	-0.78 + j0.07
2150.0	2.21	114.5	-0.32 + j0.71
2300.0	2.57	55.4	0.42 + j0.61
2450.0	3.25	-5.1	0.69 - j0.06
2600.0	3.86	-74.3	0.17 - j0.62
2750.0	4.44	-156.0	-0.55 - j0.24
2900.0	4.42	119.8	-0.30 + j0.52
3050.0	3.98	46.6	0.43 + j0.46
3200.0	3.89	-14.2	0.62 - j0.16
3350.0	3.89	-66.5	0.25 - j0.59
3500.0	4.15	-120.7	-0.32 - j0.53
3650.0	5.02	175.9	-0.56 + j0.04
3800.0	8.22	99.0	-0.06 + j0.38
3950.0	8.95	9.5	0.35 + j0.06
4100.0	6.37	-79.5	0.09 - j0.47
4250.0	4.35	-147.2	-0.51 - j0.33
4400.0	3.49	157.8	-0.62 + j0.25
4550.0	3.37	108.4	-0.21 + j0.64
4700.0	3.90	58.8	0.33 + j0.55
4850.0	5.55	1.4	0.53 + j0.01
5000.0	6.59	-82.6	0.06 - j0.46
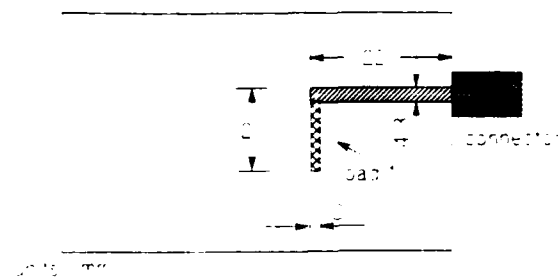
Figure 36.   Measurement of the Load 1 (Fixture B)

Table 8.   THE MEASUREMENT OF THE LOAD 1 (FIXTURE B)

Freq.(MHz)	dB (loss)	Angle(deg.)	Γ_m
2000.0	1.97	-117.8	-0.37 - j0.71
2150.0	1.89	-176.2	-0.80 - j0.05
2300.0	2.00	130.2	-0.51 + j0.61
2450.0	2.27	81.9	0.11 + j0.76
2600.0	2.40	34.8	0.62 + j0.43
2750.0	2.62	-13.9	0.72 - j0.18
2900.0	3.04	-67.3	0.27 - j0.65
3050.0	3.87	-130.3	-0.41 - j0.49
3200.0	5.05	151.6	-0.49 + j0.27
3350.0	5.41	64.0	0.24 + j0.48
3500.0	4.91	-11.7	0.56 - j0.12
3650.0	3.87	-67.6	0.24 - j0.59
3800.0	2.90	-118.9	-0.35 - j0.63
3950.0	2.55	-166.3	-0.72 - j0.18
4100.0	2.68	147.0	-0.62 + j0.40
4250.0	3.33	96.3	-0.07 + j0.68
4400.0	4.95	36.4	0.46 + j0.34
4550.0	7.33	-43.4	0.31 - j0.30
4700.0	7.51	-139.7	-0.32 - j0.27
4850.0	5.35	143.6	-0.43 + j0.32
5000.0	3.67	87.9	0.02 + j0.65

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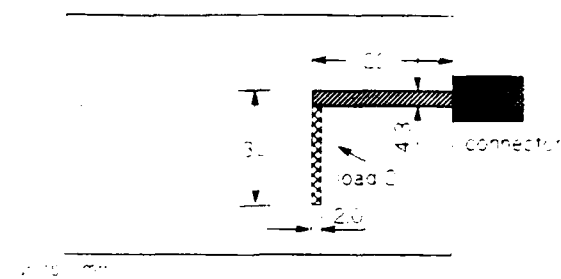
Figure 37. Measurement of the Load 2 (Fixture B)

Table 9. THE MEASUREMENT OF THE LOAD 2 (FIXTURE B)

Freq.(MHz)	dB (loss)	Angle(deg.)	Γ_m
2000.0	2.32	-26.9	0.68 - j0.35
2150.0	2.46	-91.9	-0.02 - j0.75
2300.0	2.44	-155.5	-0.69 - j0.31
2450.0	2.51	147.3	-0.63 + j0.40
2600.0	2.41	96.6	-0.09 + j0.75
2750.0	2.25	50.1	0.50 + j0.59
2900.0	2.35	6.9	0.76 + j0.09
3050.0	2.28	-35.9	0.62 - j0.45
3200.0	2.51	-78.5	0.15 - j0.73
3350.0	2.69	-123.9	-0.41 - j0.61
3500.0	3.25	-175.1	-0.69 - j0.06
3650.0	4.27	126.2	-0.36 + j0.49
3800.0	5.24	56.1	0.31 + j0.45
3950.0	5.38	-20.6	0.50 - j0.19
4100.0	4.49	-90.2	0.00 - j0.60
4250.0	3.49	-147.9	-0.57 - j0.36
4400.0	2.76	163.0	-0.70 + j0.21
4550.0	2.43	118.9	-0.37 + j0.66
4700.0	2.36	77.5	0.16 + j0.74
4850.0	2.55	36.2	0.60 + j0.44
5000.0	3.32	-8.6	0.67 - j0.10
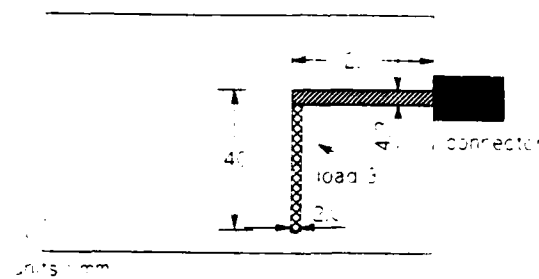
Figure 38.   Measurement of the Load 3 (Fixture B)

Table 10.   THE MEASUREMENT OF THE LOAD 3 (FIXTURE B)

Freq.(MHz)	dB (loss)	Angle(deg.)	Γ
2000.0	1.41	78.5	0.17 − j0.83
2150.0	1.71	28.1	0.72 − j0.39
2300.0	2.16	-26.2	0.70 - j0.34
2450.0	2.48	-84.3	0.07 - j0.75
2600.0	2.69	-145.9	-0.61 - j0.41
2750.0	2.85	152.4	-0.64 − j0.33
2900.0	2.85	94.8	-0.06 + j0.72
3050.0	2.75	43.2	0.53 + j0.50
3200.0	2.77	-2.9	0.73 - j0.04
3350.0	2.68	-44.3	0.53 - j0.51
3500.0	2.68	-82.4	0.10 - j0.73
3650.0	1.93	-121.1	-0.41 - j0.69
3800.0	1.91	-162.1	-0.76 - j0.25
3950.0	2.02	157.0	-0.73 + j0.31
4100.0	2.42	113.2	-0.30 + j0.70
4250.0	3.21	64.6	0.30 + j0.62
4400.0	4.49	7.5	0.59 + j0.08
4550.0	5.70	-60.8	0.25 - j0.45
4700.0	5.80	-134.9	-0.30 - j0.36
4850.0	4.89	158.8	-0.53 − j0.21
5000.0	3.72	105.1	-0.17 + j0.63

APPENDIX B.   THE S-PARAMETERS OF THE FIXTURES

Table 11.   THE S - PARAMETERS OF FIXTURE A

Freq.(MHz)	A_{11}	A_{12}	A_{22}
2000.0	-0.130 + j0.082	0.837 - j0.143	0.132 + j0.029
2150.0	-0.064 + j0.153	0.668 - j0.499	0.139 - j0.019
2300.0	0.026 + j0.165	0.355 - j0.738	0.130 - j0.080
2450.0	0.099 + j0.125	0.021 + j0.802	0.100 - j0.147
2600.0	0.141 + j0.069	0.380 + j0.701	0.034 - j0.178
2750.0	0.151 - j0.007	0.653 + j0.443	-0.018 - j0.180
2900.0	0.091 - j0.063	0.777 + j0.087	-0.032 - j0.128
3050.0	0.048 - j0.055	0.717 - j0.287	-0.003 - j0.074
3200.0	0.042 - j0.026	0.485 - j0.576	0.060 - j0.037
3350.0	0.098 - j0.025	0.151 - j0.720	0.180 - j0.031
3500.0	0.137 - j0.113	0.199 + j0.679	0.288 - j0.088
3650.0	0.054 - j0.265	0.470 + j0.482	0.330 - j0.184
3800.0	-0.148 - j0.261	0.579 + j0.214	0.327 - j0.254
3950.0	-0.258 - j0.163	0.625 - j0.036	0.321 - j0.239
4100.0	-0.334 + j0.061	0.581 - j0.305	0.299 - j0.322
4250.0	-0.256 + j0.288	0.318 - j0.506	0.442 - j0.181
4400.0	0.174 + j0.317	0.008 - j0.477	0.713 - j0.044
4550.0	-0.502 - j0.872	0.225 - j1.580	1.743 - j1.374
4700.0	-0.064 - j0.531	0.670 - j0.309	0.034 - j0.761
4850.0	0.183 + j0.229	0.651 + j0.057	0.137 - j0.304
5000.0	0.062 + j0.136	0.646 - j0.289	0.219 - j0.013

Table 12.   THE S - PARAMETERS OF FIXTURE B

Freq.(MHz)	B_{11}	B_{12}	B_{22}
2000.0	-0.060 + j0.107	0.342 - j0.834	0.036 - j0.076
2150.0	-0.007 + j0.116	0.057 - j0.892	0.008 - j0.081
2300.0	0.027 + j0.100	0.230 + j0.850	-0.032 - j0.085
2450.0	0.049 + j0.091	0.475 + j0.723	-0.083 - j.082
2600.0	0.080 + j0.084	0.669 + j0.533	-0.115 - j0.075
2750.0	0.124 + j0.063	0.792 - j0.291	-0.125 - j0.062
2900.0	0.152 + j0.007	0.831 + j0.028	-0.136 - j0.029
3050.0	0.158 - j0.073	0.788 - j0.229	-0.125 - j0.007
3200.0	0.106 - j0.143	0.669 - j0.451	-0.110 + j0.016
3350.0	0.026 - j0.168	0.494 - j0.630	-0.064 + j0.036
3500.0	-0.035 - j0.149	0.268 - j0.741	0.016 + j0.059
3650.0	-0.092 - j0.112	0.033 - j0.790	0.108 + j0.019
3800.0	-0.076 - j0.072	0.230 + j0.762	0.165 + j0.018
3950.0	-0.069 - j0.097	0.468 + j0.633	0.261 + j0.019
4100.0	-0.137 - j0.157	0.636 + j0.412	0.389 + j0.014
4250.0	-0.331 - j0.130	0.681 + j0.135	0.543 + j0.018
4400.0	-0.572 + j0.161	0.478 - j0.116	0.808 + j0.024
4550.0	-0.114 + j1.171	1.062 + j0.589	1.625 - j0.527
4700.0	0.230 - j0.171	0.577 - j0.759	0.163 - j0.968
4850.0	-0.065 + j0.166	0.306 - j0.676	0.219 - j0.546
5000.0	0.124 + j0.326	0.091 - j0.685	0.291 - j0.446

APPENDIX C. THE S-PARAMETERS OF THE EMBEDDED AND DE-EMBEDDED 51 OHM RESISTOR

Table 13. THE THEORETICAL S - PARAMETERS OF THE 51 OHM RESISTOR IN DB UNITS.

Freq.(MHz)	S_{11}	S_{12}	S_{21}	S_{22}
2000.0	6.11	4.27	4.27	6.11
2150.0	5.82	4.37	4.37	5.82
2300.0	5.54	4.47	4.47	5.54
2450.0	5.28	4.58	4.58	5.28
2600.0	5.02	4.69	4.69	5.02
2750.0	4.78	4.81	4.81	4.78
2900.0	4.55	4.93	4.93	4.55
3050.0	4.34	5.05	5.05	4.34
3200.0	4.13	5.17	5.17	4.13
3350.0	3.94	5.30	5.30	3.94
3500.0	3.76	5.43	5.43	3.76
3650.0	3.58	5.56	5.56	3.58
3800.0	3.42	5.69	5.69	3.42
3950.0	3.27	5.82	5.82	3.27
4100.0	3.12	5.95	5.95	3.12
4250.0	2.99	6.09	6.09	2.99
4400.0	2.86	6.22	6.22	2.86
4550.0	2.73	6.36	6.36	2.73
4700.0	2.62	6.49	6.49	2.62
4850.0	2.51	6.63	6.63	2.51
5000.0	2.41	6.76	6.76	2.41

Table 14. THE S - PARAMETERS OF BOTH FIXTURE AND 51 OHM RESISTOR

Freq.(MHz)	M_{11}	M_{12}	M_{21}	M_{22}
2000.0	11.14	4.40	4.60	6.45
2150.0	11.38	4.64	4.71	6.27
2300.0	10.18	4.90	4.80	6.05
2450.0	8.47	5.36	5.35	5.86
2600.0	7.13	5.87	5.84	5.51
2750.0	6.35	6.30	6.25	4.99
2900.0	6.21	6.99	6.99	4.68
3050.0	6.51	7.54	7.49	4.48
3200.0	7.33	7.32	7.25	4.43
3350.0	8.92	7.04	6.65	4.94
3500.0	11.29	7.10	5.81	5.75
3650.0	12.01	6.46	6.31	6.18
3800.0	11.59	7.30	7.25	6.91
3950.0	9.15	6.45	6.90	7.83
4100.0	6.27	6.35	6.56	9.07
4250.0	5.53	6.00	6.25	1.78
4400.0	6.07	5.61	5.85	12.72
4550.0	7.54	5.30	5.50	12.53
4700.0	9.91	5.34	5.39	10.00
4850.0	10.46	5.70	5.66	7.82
5000.0	11.95	6.10	6.05	6.53

Table 15.   THE DE - EMBEDDED OUTPUT OF 51 OHM RESISTOR DEVICE UNDER TEST.

Freq.(MHz)	S_{11}	S_{12}	S_{21}	S_{22}
2000.0	6.35	3.62	3.82	4.92
2150.0	5.72	3.97	3.64	5.84
2300.0	5.12	3.97	3.97	4.74
2450.0	4.57	3.18	3.17	3.75
2600.0	4.22	3.39	3.36	3.04
2750.0	3.61	3.66	3.61	4.74
2900.0	3.87	4.27	4.27	3.77
3050.0	3.64	4.91	4.86	2.91
3200.0	3.19	4.51	4.44	2.67
3350.0	3.03	4.16	3.77	2.41
3500.0	3.16	4.72	4.43	3.79
3650.0	3.62	4.65	4.50	4.45
3800.0	3.91	4.56	4.51	3.72
3950.0	3.35	5.38	4.83	2.73
4100.0	2.66	5.06	5.27	4.66
4250.0	3.45	5.71	5.46	5.31
4400.0	4.11	5.83	6.07	2.52
4550.0	3.17	6.36	6.56	2.07
4700.0	2.25	6.73	6.68	3.34
4850.0	2.08	6.73	6.69	2.95
5000.0	2.11	6.96	6.91	2.02

APPENDIX D. THE S-PARAMETERS OF THE FIXTURE, FILTER EMBEDDED, FILTER WITHOUT FIXTURES AND FILTER DE-EMBEDDED

Table 16. THE S - PARAMETERS OF THE FIXTURE

Freq.(MHz)	S_{11}	S_{12}	S_{22}
6000.0	-0.08 + j0.17	0.81 + j0.55	-0.09 + j0.13
6320.0	-0.09 + j0.04	0.76 - j0.61	-0.17 + j0.10
6640.0	-0.06 + j0.04	-0.39 - j0.90	-0.03 + j0.12
6960.0	-0.05 + j0.03	-0.98 + j0.16	-0.08 + j0.07
7280.0	-0.19 + j0.03	-0.08 + j0.97	-0.18 + j0.15
7600.0	-0.13 + j0.14	0.92 + j0.36	-0.05 + j0.18
7920.0	0.01 + j0.07	0.57 - j0.81	0.01 + j0.11
8240.0	-0.07 + j0.00	-0.63 - j0.76	0.02 + j0.11
8560.0	-0.12 + j0.04	-0.90 + j0.42	0.03 - j0.01
8880.0	-0.10 + j0.07	0.18 + j0.97	-0.11 - j0.03
9200.0	0.00 + j0.19	0.96 + j0.06	-0.03 + j0.20
9520.0	0.10 + j0.14	0.33 - j0.91	0.11 + j0.11
9840.0	0.11 - j0.04	-0.81 - j0.55	-0.02 - j0.09
10160.0	0.12 - j0.19	-0.74 + j0.66	-0.03 - j0.03
10480.0	-0.03 - j0.13	0.42 + j0.88	0.03 + j0.02
10800.0	-0.02 - j0.14	0.96 - j0.18	-0.02 - j0.09
11120.0	-0.18 - j0.12	0.06 - j0.98	-0.16 + j0.03
11440.0	-0.14 - j0.03	-0.91 - j0.33	-0.08 + j0.02
11760.0	-0.02 - j0.14	-0.57 + j0.79	-0.04 - j0.04
12080.0	-0.04 - j0.04	0.63 + j0.75	0.04 + j0.06
12400.0	-0.02 - j0.10	0.85 - j0.45	-0.02 - j0.04

Table 17.   THE S - PARAMETERS OF FILTER + FIXTURE

Freq.(MHz)	S_{11}	S_{12}	S_{22}
6000.0	-0.79 - j0.45	0.00 + j0.00	0.54 + j0.75
6320.0	0.89 - j0.14	0.00 + j0.00	-0.36 - j0.82
6640.0	-0.65 + j0.62	0.01 + j0.01	-0.02 + j0.90
6960.0	0.11 - j0.91	0.01 + j0.01	0.05 - j0.89
7280.0	0.62 + j0.64	0.01 + j0.01	-0.24 + j0.90
7600.0	-0.80 + j0.45	-0.02 + j0.02	0.02 - j0.91
7920.0	0.11 - j0.24	-0.30 + j0.86	0.00 + j0.25
8240.0	-0.13 + j0.20	-0.34 + j0.86	-0.01 - j0.15
8560.0	-0.01 + j0.36	-0.82 + j0.24	0.15 + j0.27
8880.0	0.01 + j0.04	-0.61 - j0.69	-0.01 - j0.05
9200.0	0.31 + j0.01	0.56 - j0.65	0.03 + j0.31
9520.0	0.27 + j0.29	0.76 + j0.41	-0.28 - j0.06
9840.0	-0.16 + j0.22	-0.48 + j0.76	0.07 - j0.23
10160.0	-0.06 + j0.23	-0.73 - j0.50	0.00 + j0.29
10480.0	-0.06 - j0.26	0.47 - j0.76	-0.26 - j0.03
10800.0	0.21 - j0.02	0.79 + j0.46	-0.05 - j0.19
11120.0	-0.17 - j0.07	-0.45 + j0.78	-0.14 - j0.02
11440.0	-0.14 + j0.00	-0.83 - j0.37	0.14 + j0.01
11760.0	0.19 + j0.07	0.16 - j0.86	0.17 + j0.05
12080.0	0.25 - j0.24	0.72 - j0.28	-0.48 - j0.13
12400.0	-0.15 + j0.70	0.74 + j0.18	0.59 + j0.12

Table 18.   THE S - PARAMETERS OF FILTER WITHOUT FIX-
TURES IN DB UNITS

Freq.(MHz)	S_{11}	S_{12}	S_{21}	S_{22}
6000.0	1.57	83.91	88.79	0.62
6320.0	1.96	91.38	105.37	1.69
6640.0	0.47	75.81	78.12	0.19
6960.0	0.87	69.94	69.39	0.85
7280.0	0.77	54.40	51.94	0.86
7600.0	0.70	29.99	31.60	1.12
7920.0	10.17	0.57	0.50	9.15
8240.0	11.32	0.15	0.16	12.00
8560.0	8.62	0.45	0.45	10.05
8880.0	15.77	0.20	0.08	13.81
9200.0	9.66	0.40	0.20	9.88
9520.0	10.97	0.25	0.33	11.81
9840.0	9.65	0.27	0.66	9.11
10160.0	8.39	0.45	0.40	10.81
10480.0	12.78	0.15	0.20	12.01
10800.0	11.35	0.43	0.45	11.87
11120.0	13.64	0.30	0.20	14.39
11440.0	10.28	0.31	0.46	16.09
11760.0	15.44	0.60	0.41	15.84
12080.0	7.35	1.40	1.10	9.98
12400.0	8.85	1.45	0.96	11.51

Table 19.   THE DE-EMBEDDED OUTPUT OF FILTER UNDER
            TEST

Freq.(MHz)	S_{11}	S_{12}	S_{21}	S_{22}
6000.0	1.58	37.03	90.64	0.28
6320.0	2.03	41.18	91.12	1.15
6640.0	1.11	41.62	76.82	0.14
6960.0	2.32	59.94	71.12	0.90
7280.0	0.68	51.99	53.34	1.21
7600.0	0.21	30.06	31.45	0.92
7920.0	10.50	1.27	1.51	9.64
8240.0	10.99	0.59	0.60	13.25
8560.0	7.97	1.25	1.18	10.17
8880.0	12.83	1.12	0.55	10.50
9200.0	9.57	1.36	0.70	10.77
9520.0	8.80	0.35	0.94	9.70
9840.0	10.83	0.11	0.81	8.38
10160.0	7.58	0.74	0.90	10.05
10480.0	11.96	0.62	0.75	9.76
10800.0	12.39	0.67	0.73	9.99
11120.0	11.49	0.14	0.20	9.78
11440.0	8.94	0.38	0.76	15.48
11760.0	13.73	0.76	0.94	14.58
12080.0	8.20	2.11	1.41	6.85
12400.0	8.41	1.77	1.38	7.79

APPENDIX E. FORTRAN PROGRAM FOR DE-EMBEDDING THE 51 OHM RESISTOR

```
DIMENSION X(200),MDB11(200),PSE11(200)
         MDB12(200),PSE12(200)
         MDB21(200),PSE21(200)
         MDB22(200),PSE22(200),MDB222(200)
REAL MDB11,MDB12,MDB21,MDB22,MDB222
     MAG11,MAG12,MAG21,MAG22
     IM11,IM12,IM21,IM22
COMPLEX S11,S12,S21,S22,A12A21,B12B21
        A11,A12,A21,A22,AA121,A12B12,A21B21
        B11,B12,B21,B22,BB121
        M11,M12,M21,M22
        E,FF,G,H,N,AABB
PI=4.*ATAN(1.)

DO 10 I=1,21
  F=18.5*10.**8+1.5*10.**8*FLOAT(I)
X(I)=F/1000000.

CALL FIX1(A11,A12,A21,A22,A12A21,AMAG12,PSEA12,F)

CALL TMFS(M11,M12,M21,M22,F)

CALL FIX2(B11,B12,B21,B22,B12B21,BMAG12,PSEB12,F)


TMAG=AMAG12*BMAG12
TPSE=PSEA12+PSEB12
XRE=TMAG*COS(TPSE)
XIM=TMAG*SIN(TPSE)
A12B12=CMPLX(XRE,XIM)
A21B21=A12B12

E=M12/(A12B12)
FF=M21/(A21B21)
G=(M11-A11)/A12A21
H=(M22-B22)/B12B21
N=(1.+A22*G)*(1.+B11*H)-A22*B11*E*FF


S11=(G*(1.+B11*H)-B11*E*FF)/N
S12=E/N
S21=FF/N
S22=(H*(1.+A22*G)-A22*E*FF)/N


QIM1=AIMAG(S11)
```

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```
                  QRE1=REAL(S11)
                  QIM2=AIMAG(S12)
                  QRE2=REAL(S12)
                  QIM3=AIMAG(S21)
                  QRE3=REAL(S21)
                  QIM4=AIMAG(S22)
                  QRE4=REAL(S22)

      FIND A MAGNITUDE AND PHASE(ANGLE)

                  MAG11=CABS(S11)
                  MAG12=CABS(S12)
                  MAG21=CABS(S21)
                  MAG22=CABS(S22)
                  MDB11(I)=ABS(20*ALOG10(MAG11))
                  MDB12(I)=ABS(20*ALOG10(MAG12))
                  MDB21(I)=ABS(20*ALOG10(MAG21))
                  MDB22(I)=ABS(20*ALOG10(MAG22))
                  PSE11(I)=ATAN2(QIM1,QRE1)*180./PI
                  PSE12(I)=ATAN2(QIM2,QRE2)*180./PI
                  PSE21(I)=ATAN2(QIM3,QRE3)*180./PI
                  PSE22(I)=ATAN2(QIM4,QRE4)*180./PI

                  WRITE(6,101) X(I),MDB11(I),MDB12(I),MDB21(I),MDB22(I),
          1                    PSE11(I),PSE12(I),PSE21(I),PSE22(I)
      101   FORMAT(F6.0,8(1X,F7.2))
      10    CONTINUE
            END




      C     ****************************************
            SUBROUTINE TMFS (D11,D12,D21,D22,F)
      C     ****************************************

            COMPLEX D11,D12,D21,D22
            PI=4.*ATAN(1.)

         INPUT DATA FILE IS DISK 9
         ( BOTH FIXTURE + DEVICE )

            READ(9,21)DB11,ANG11,DB21,ANG21,DB12,ANG12,DB22,ANG22
      21    FORMAT(8(F7.2))
            V11=10.**(-DB11/20.)
            V12=10.**(-DB12/20.)
            V21=10.**(-DB21/20.)
            V22=10.**(-DB22/20.)
            RAD11=PI/180.*ANG11
            RAD12=PI/180.*ANG12
            RAD21=PI/180.*ANG21
            RAD22=PI/180.*ANG22

            QRE11=V11*COS(RAD11)
            QRE12=V12*COS(RAD12)
            QRE21=V21*COS(RAD21)
```

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```fortran
      QRE22=V22*COS(RAD22)
      QIM11=V11*SIN(RAD11)
      QIM12=V12*SIN(RAD12)
      QIM21=V21*SIN(RAD21)
      QIM22=V22*SIN(RAD22)

      D11=CMPLX(QRE11,QIM11)
      D12=CMPLX(QRE12,QIM12)
      D21=CMPLX(QRE21,QIM21)
      D22=CMPLX(QRE22,QIM22)

      RETURN
      END


C     ********************************************************
      SUBROUTINE FIX1(S11,S12,S21,S22,SS,SMAG12,SPSE12,F)
C     ********************************************************

      FOR FIXTURE A

      COMPLEX A(3,3),H(3,3),B(1,3),C(3),D(3,3),SS121
      COMPLEX S11,S12,S21,S22,SS

      CALL DATA1(A,B,F)

      CALL CPX(A)

         DO 10 I=1,3
           C(I)=A(1,I)*B(1,1)+A(2,I)*B(1,2)+A(3,I)*B(1,3)
10         CONTINUE

      S11=C(1)
      S22=C(2)
      SS121=C(3)
      SS=S11*S22-SS121

      SIM=AIMAG(SS)
      SRE=REAL(SS)
      SMAGSS=CABS(SS)
      PSESS=ATAN2(SIM,SRE)
      SPSE12=0.5*PSESS
      SPSE21=SPSE12
      SMAG12=SMAGSS**0.5
      SMAG21=SMAG12

      S12=(S11*S22-SS121)**0.5
      S21=S12
      RETURN
      END


C     ************************
      SUBROUTINE DATA1(D,B,F)
C     ************************
      COMPLEX D(3,3),B(1,3),RIN1,RIN2,RIN3,RL1,RL2,RL3
```

```
         CALL RLOAD(RL1,RL2,RL3,F)

         CALL RIN(RIN1,RIN2,RIN3)

          D(1,1)=1./RL1
          D(1,2)=1./RL2
          D(1,3)=1./RL3
          D(2,1)=RIN1
          D(2,2)=RIN2
          D(2,3)=RIN3
          D(3,1)=(-1.,.0)
          D(3,2)=(-1.,.0)
          D(3,3)=(-1.,.0)
          B(1,1)=RIN1/RL1
          B(1,2)=RIN2/RL2
          B(1,3)=RIN3/RL3
          RETURN
          END


C        ***********************************
         SUBROUTINE RIN(RIN1,RIN2,RIN3)
C        ***********************************

         COMPLEX RIN1,RIN2,RIN3

         CALL F1DAT(DB111,ANG111,DB112,ANG112,DB113,ANG113)

         PI=4.*ATAN(1.)
   INPUT DATA FILE IS DISK8
   (FIXTURE 1 ONLY)
         V111=10.**(-DB111/20.)
         V112=10.**(-DB112/20.)
         V113=10.**(-DB113/20.)
         RAD111=PI/180.*ANG111
         RAD112=PI/180.*ANG112
         RAD113=PI/180.*ANG113

         QRE111=V111*COS(RAD111)
         QRE112=V112*COS(RAD112)
         QRE113=V113*COS(RAD113)
         QIM111=V111*SIN(RAD111)
         QIM112=V112*SIN(RAD112)
         QIM113=V113*SIN(RAD113)

         RIN1=CMPLX(QRE111,QIM111)
         RIN2=CMPLX(QRE112,QIM112)
         RIN3=CMPLX(QRE113,QIM113)
         RETURN
         END


C        *********************************************************
         SUBROUTINE F1DAT(DB111,ANG111,DB112,ANG112,DB113,ANG113)
C        *********************************************************
```

```
            INPUT DATA FILE IS DISK 8
               (For FIXTURE A)

            READ(8,20)DB111,ANG111,DB112,ANG112,DB113,ANG113
    20      FORMAT(6(F7.2))
            RETURN
            END


C           ***************************************************
            SUBROUTINE FIX2(S11,S12,S21,S22,SSS,SMAG12,SPSE12,F)
C           ***************************************************

            FOR FIXTURE 2

            COMPLEX A(3,3),H(3,3),B(1,3),C(3),D(3,3),SS121
            COMPLEX S11,S12,S21,S22,SSS

            CALL DATA2(A,B,F)

            CALL CPX(A)

               DO 10 I=1,3
                  C(I)=A(1,I)*B(1,1)+A(2,I)*B(1,2)+A(3,I)*B(1,3)
    10         CONTINUE
            S11=C(1)
            S22=C(2)
            SS121=C(3)
            SSS=S11*S22-SS121

            SIM=AIMAG(SSS)
            SRE=REAL(SSS)
            SMAGSS=CABS(SSS)
            PSESS=ATAN2(SIM,SRE)
            SPSE12=0.5*PSESS
            SPSE21=SPSE12
            SMAG12=SMAGSS**0.5
            SMAG21=SMAG12

            S12=(S11*S22-SS121)**0.5
            S21=S12
            RETURN
            END


C           ***************************
            SUBROUTINE DATA2(D,B,F)
C           ***************************

            COMPLEX D(3,3),B(1,3),RIN1,RIN2,RIN3,RL1,RL2,RL3

            CALL RLOAD(RL1,RL2,RL3,F)

            CALL R2IN(RIN1,RIN2,RIN3)
```

```
               D(1,1)=1./RL1
               D(1,2)=1./RL2
               D(1,3)=1./RL3
               D(2,1)=RIN1
               D(2,2)=RIN2
               D(2,3)=RIN3
               D(3,1)=(-1.,.0)
               D(3,2)=(-1.,.0)
               D(3,3)=(-1.,.0)
               B(1,1)=RIN1/RL1
               B(1,2)=RIN2/RL2
               B(1,3)=RIN3/RL3
               RETURN
               END


       C       *********************************
               SUBROUTINE R2IN(RIN1,RIN2,RIN3)
       C       *********************************

               COMPLEX RIN1,RIN2,RIN3

               CALL F2DAT(DB111,ANG111,DB112,ANG112,DB113,ANG113)

               PI=4.*ATAN(1.)

               V111=10.**(-DB111/20.)
               V112=10.**(-DB112/20.)
               V113=10.**(-DB113/20.)
               RAD111=PI/180.*ANG111
               RAD112=PI/180.*ANG112
               RAD113=PI/180.*ANG113

               QRE111=V111*COS(RAD111)
               QRE112=V112*COS(RAD112)
               QRE113=V113*COS(RAD113)
               QIM111=V111*SIN(RAD111)
               QIM112=V112*SIN(RAD112)
               QIM113=V113*SIN(RAD113)

               RIN1=CMPLX(QRE111,QIM111)
               RIN2=CMPLX(QRE112,QIM112)
               RIN3=CMPLX(QRE113,QIM113)
               RETURN
               END


       C       ****************************************************************
               SUBROUTINE F2DAT(DB111,ANG111,DB112,ANG112,DB113,ANG113)
       C       ****************************************************************

               INPUT DATA FILE IS DISK 10
                   (For FIXTURE B)

               READ(10,20)DB111,ANG111,DB112,ANG112,DB113,ANG113
       20      FORMAT(6(F7.2))
```

```fortran
      RETURN
      END


C     ***************
      SUBROUTINE CPX(A)
C     ***************

      INTEGER IP(3)
      COMPLEX A(3,3),W(3),DET(2)

      CALL CGEFA(A,3,3,IP,INFO)

      CALL CGEDI(A,3,3,IP,DET,W,01)

      RETURN
      END


C     *********************************
      SUBROUTINE RLOAD(RL1,RL2,RL3,F)
C     *********************************

      COMPLEX RL1,RL2,RL3,ZO,ZL1,ZL2,ZL3
      REAL L1,L2,L3
      PI=4.*ATAN(1.)
      C=3.*10**8
      ZOS=68.2
      ERE=2.833
      ERES=(ERE)**0.5
      L1=0.04
      L2=0.03
      L3=0.02

      A1=COS(2.*PI*F*L1*ERES/C)
      B1=SIN(2.*PI*F*L1*ERES/C)
      A2=COS(2.*PI*F*L2*ERES/C)
      B2=SIN(2.*PI*F*L2*ERES/C)
      A3=COS(2.*PI*F*L3*ERES/C)
      B3=SIN(2.*PI*F*L3*ERES/C)
      R1=-ZOS*(A1/B1)
      R2=-ZOS*(A2/B2)
      R3=-ZOS*(A3/B3)
      ZL1=CMPLX(0.,R1)
      ZL2=CMPLX(0.,R2)
      ZL3=CMPLX(0.,R3)
      ZO=CMPLX(50.,0.)
      RL1=(ZL1-ZO)/(ZL1+ZO)
      RL2=(ZL2-ZO)/(ZL2+ZO)
      RL3=(ZL3-ZO)/(ZL3+ZO)
      RETURN
      END



C     ***********************************
```

THE INPUT DATA FILE FOR DISK 8
3 DIFFERENT LOAD FOR FIXTURE A
****

```
3.07    22.7   2.28    98.2   2.14   175.1
3.82   -63.1   2.89    29.5   2.21   114.5
3.79  -153.9   3.77   -49.2   2.57    55.4
3.46   126.4   4.12  -138.0   3.25    -5.1
3.20    60.5   3.75   136.6   3.86   -74.3
3.33    -1.7   3.31    65.1   4.44  -156.0
4.04   -69.9   3.40     4.9   4.42   119.8
5.39  -152.8   3.60   -54.2   3.98    46.6
6.17   107.6   4.55  -119.0   3.89   -14.2
5.32    17.1   5.78   159.8   3.89   -66.5
4.65   -51.0   6.39    61.8   4.15  -120.7
3.97  -111.9   5.76   -25.5   5.02   175.9
4.89  -175.9   5.70   -89.0   8.22    99.0
7.73   104.5   4.69  -134.2   8.95     9.5
7.36   -17.1   3.91   173.7   6.37   -79.5
6.70  -121.4   4.48   117.4   4.35  -147.2
4.59   170.4   6.84    47.9   3.49   157.8
4.12   114.2   8.48   -61.4   3.37   108.4
4.88    58.9   7.57  -174.8   3.90    58.8
7.91    -9.1   4.92   115.1   5.55     1.4
8.42  -137.9   3.99    62.0   6.59   -82.6
```

****
THE INPUT DATA FILE FOR DISK 9
BOTH FIXTURE AND 51 OHM RES.
****

```
11.14    -9.3   4.60    51.0   4.40    51.4   6.45  -150.2
11.38   -81.2   4.71    -1.5   4.64     0.2   6.27   173.1
10.18  -154.3   4.80   -53.9   4.90   -52.2   6.05   137.6
 8.47   143.1   5.35  -106.1   5.36  -103.3   5.86   103.2
 7.13    89.7   5.84  -152.2   5.87  -150.5   5.51    70.3
 6.35    41.0   6.25   159.0   6.30   160.2   4.99    37.0
 6.21    -5.3   6.99   112.1   6.99   113.1   4.68     3.0
 6.51   -51.8   7.49    66.6   7.54    68.4   4.48   -30.7
 7.33  -102.0   7.25    19.4   7.32    22.0   4.43   -65.6
 8.92  -163.3   6.65   -26.9   7.04   -25.9   4.94  -101.3
11.29   112.5   5.81   -79.3   7.10   -73.4   5.75  -133.5
12.01    12.6   6.31  -133.3   6.46  -121.3   6.18  -165.5
11.59   -61.5   7.25   179.3   7.30   174.6   6.91   160.7
 9.15   -93.7   6.90   135.8   6.45   133.3   7.83   125.8
 6.27  -142.5   6.56    85.4   6.35    83.2   9.07    87.1
 5.53   169.5   6.25    34.5   6.00    34.1   1.78    41.0
 6.07   126.3   5.85   -17.5   5.61   -14.6  12.72   -22.9
 7.54    87.7   5.50   -69.5   5.30   -64.8  12.53  -104.0
 9.91    51.8   5.39  -121.9   5.34  -118.0  10.00  -174.9
10.46    23.7   5.66  -176.7   5.70  -171.1   7.82   131.2
11.95    44.3   6.05   131.4   6.10   134.9   6.53    87.5
```

```
***********************************
THE INPUT DATA FILE FOR DISK 10
3 DIFFERENT LOAD FOR FIXTURE B
***********************************


1.97 -117.8    2.32  -26.9    1.41   78.5
1.89 -176.2    2.46  -91.9    1.71   28.1
2.00  130.2    2.44 -155.5    2.16  -26.2
2.27   81.9    2.51  147.3    2.48  -84.3
2.40   34.8    2.41   96.6    2.69 -145.9
2.62  -13.9    2.25   50.1    2.85  152.4
3.04  -67.3    2.35    6.9    2.85   94.8
3.87 -130.3    2.28  -35.9    2.75   43.2
5.05  151.6    2.51  -78.5    2.77   -2.9
5.41   64.0    2.69 -123.9    2.68  -44.3
4.91  -11.7    3.25 -175.1    2.68  -82.4
3.87  -67.6    4.27  126.2    1.93 -121.1
2.90 -118.9    5.24   56.1    1.91 -162.1
2.55 -166.3    5.38  -20.6    2.02  157.0
2.68  147.0    4.49  -90.2    2.42  113.2
3.33   96.3    3.49 -147.9    3.21   64.6
4.95   36.4    2.76  163.0    4.49    7.5
7.33  -43.4    2.43  118.9    5.70  -60.8
7.51 -139.7    2.36   77.5    5.80 -134.9
5.35  143.6    2.55   36.2    4.89  158.8
3.67   87.9    3.32   -8.6    3.72  105.1
```

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APPENDIX F.   FORTRAN PROGRAM FOR DE-EMBEDDING THE FILTER

```
DIMENSION X(21),MDB11(21),PSE11(21)
      MDB12(21),PSE12(21)
      MDB21(21),PSE21(21)
      MDB22(21),PSE22(21)
REAL MDB11,MDB12,MDB21,MDB22
     MAG11,MAG12,MAG21,MAG22
     IM11,IM12,IM21,IM22
COMPLEX S11,S12,S21,S22
      A11,A12,A21,A22
      B11,B12,B21,B22,W
      D11,D12,D21,D22
      C11,C12,C21,C22
      F11,F12,F21,F22
      M11,M12,M21,M22
      H11,H12,H21,H22

PI=4.*ATAN(1.)

DO 10 I=1,21

INPUT DATA FILE IS DISK8
(FIXTURE 1 ONLY)

      READ(8,20)DB11,DB12,DB21,DB22,ANG11,ANG12,ANG21,ANG22
20    FORMAT(8(F7.2))

V11=10.**(-DB11/20.)
V12=10.**(-DB12/20.)
V21=10.**(-DB21/20.)
V22=10.**(-DB22/20.)
RAD11=PI/180.*ANG11
RAD12=PI/180.*ANG12
RAD21=PI/180.*ANG21
RAD22=PI/180.*ANG22

QRE11=V11*COS(RAD11)
QRE12=V12*COS(RAD12)
QRE21=V21*COS(RAD21)
QRE22=V22*COS(RAD22)
QIM11=V11*SIN(RAD11)
QIM12=V12*SIN(RAD12)
QIM21=V21*SIN(RAD21)
QIM22=V22*SIN(RAD22)

A11=CMPLX(QRE11,QIM11)
A12=CMPLX(QRE12,QIM12)
```

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```fortran
      A21=CMPLX(QRE21,QIM21)
      A22=CMPLX(QRE22,QIM22)

C     "S"PARAMETERS TO "T"PARAMETERS

      B11=-(A11*A22-A12*A21)/A21
      B12= A11/A21
      B21=-A22/A21
      B22=1/A21

C     INVERSE OF FIXTURE 1 "T"PARAMETER

      W= 1/(B11*B22-B21*B12)
      C11=W*B22
      C12=-W*B21
      C21= -W*B12
      C22= W*B11

      CALL OF 'T'PARAMETERS OF BOTH FIXTURE + FILTER

      CALL TMFS(D11,D12,D21,D22,I)

C     (INVERSE OF FIXTURE 1) * (BOTH FIXTURE+DEVICE)

      H11=C11*D11+C21*D12
      H12=C12*D11+C22*D12
      H21=C11*D21+C21*D22
      H22=C12*D21+C22*D22

      CALL OF INVERSE 'T'PARAMETER OF FIXTURE 2

      CALL FIX2(F11,F12,F21,F22)

C     CASCADE OF FIXTURE 1, FILTER AND FIXTURE 2

      M11=H11*F11+H21*F12
      M12=H12*F11+H22*F12
      M21=H11*F21+H21*F22
      M22=H12*F21+H22*F22

C     "T"PARAMETERS TO "S"PARAMETERS

      S11=M12/M22
      S12= M11-(M12*M21)/M22
      S21= 1/M22
      S22= -M21/M22

      QIM1=AIMAG(S11)
      QRE1=REAL(S11)
      QIM2=AIMAG(S12)
      QRE2=REAL(S12)
      QIM3=AIMAG(S21)
      QRE3=REAL(S21)
      QIM4=AIMAG(S22)
      QRE4=REAL(S22)
```

```
C      DE-EMBEDDED OUTPUT

       MAG11=CABS(S11)
       MAG12=CABS(S12)
       MAG21=CABS(S21)
       MAG22=CABS(S22)
       MDB11(I)=ABS(20*ALOG10(MAG11))
       MDB12(I)=ABS(20*ALOG10(MAG12))
       MDB21(I)=ABS(20*ALOG10(MAG21))
       MDB22(I)=ABS(20*ALOG10(MAG22))
       PSE11(I)=ATAN2(QIM1,QRE1)*180./PI
       PSE12(I)=ATAN2(QIM2,QRE2)*180./PI
       PSE21(I)=ATAN2(QIM3,QRE3)*180./PI
       PSE22(I)=ATAN2(QIM4,QRE4)*180./PI

       N=5680
       X(I)=N+320.*FLOAT(I)
       WRITE(6,100) X(I),MDB11(I),MDB12(I),MDB21(I),MDB22(I),
     1                    PSE11(I),PSE12(I),PSE21(I),PSE22(I)
100    FORMAT(' ',2X,F6.0,8(1X,F7.2))
10     CONTINUE
       END




C      *********************************************
       SUBROUTINE TMFS (D11,D12,D21,D22,I)
C      *********************************************

       COMPLEX A11,A12,A21,A22
       COMPLEX D11,D12,D21,D22
       PI=4.*ATAN(1.)

       INPUT DATA FILE IS DISK 9
       (BOTH FIXTURE + DEVICE )

       READ(9,21)DB11,DB12,DB21,DB22,ANG11,ANG12,ANG21,ANG22
21     FORMAT(8(F7.2))

       V11=10.**(-DB11/20.)
       V12=10.**(-DB12/20.)
       V21=10.**(-DB21/20.)
       V22=10.**(-DB22/20.)
       RAD11=PI/180.*ANG11
       RAD12=PI/180.*ANG12
       RAD21=PI/180.*ANG21
       RAD22=PI/180.*ANG22

       QRE11=V11*COS(RAD11)
       QRE12=V12*COS(RAD12)
       QRE21=V21*COS(RAD21)
       QRE22=V22*COS(RAD22)
       QIM11=V11*SIN(RAD11)
       QIM12=V12*SIN(RAD12)
       QIM21=V21*SIN(RAD21)
       QIM22=V22*SIN(RAD22)
```

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```
                A11=CMPLX(QRE11,QIM11)
                A12=CMPLX(QRE12,QIM12)
                A21=CMPLX(QRE21,QIM21)
                A22=CMPLX(QRE22,QIM22)

                D11=-(A11*A22-A12*A21)/A21
                D12= A11/A21
                D21=-A22/A21
                D22=1/A21
                RETURN
                END


C       ****************************
        SUBROUTINE FIX2(F11,F12,F21,F22)
C       ****************************

                COMPLEX A11,A12,A21,A22
                COMPLEX B11,B12,B21,B22,W
                COMPLEX C11,C12,C21,C22
                COMPLEX F11,F12,F21,F22
                PI=4.*ATAN(1.)

                INPUT DATA FILE IS DISK 10
                (FIXTURE 2 ONLY)

                READ(10,20)DB11,DB12,DB21,DB22,ANG11,ANG12,ANG21,ANG22
20              FORMAT(8(F7.2))

                V11=10.**(-DB11/20.)
                V12=10.**(-DB12/20.)
                V21=10.**(-DB21/20.)
                V22=10.**(-DB22/20.)
                RAD11=PI/180.*ANG11
                RAD12=PI/180.*ANG12
                RAD21=PI/180.*ANG21
                RAD22=PI/180.*ANG22

                QRE11=V11*COS(RAD11)
                QRE12=V12*COS(RAD12)
                QRE21=V21*COS(RAD21)
                QRE22=V22*COS(RAD22)
                QIM11=V11*SIN(RAD11)
                QIM12=V12*SIN(RAD12)
                QIM21=V21*SIN(RAD21)
                QIM22=V22*SIN(RAD22)

                A11=CMPLX(QRE11,QIM11)
                A12=CMPLX(QRE12,QIM12)
                A21=CMPLX(QRE21,QIM21)
                A22=CMPLX(QRE22,QIM22)

                B11=-(A11*A22-A12*A21)/A21
                B12= A11/A21
```

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```
B21=-A22/A21
B22=1/A21

W= 1/(B11*B22-B21*B12)
F11=W*B22
F12=-W*B21
F21= -W*B12
F22= W*B11
RETURN
END
```

```
c     *********************************
c     The Input Data File for Disk8
c     *********************************
```

14.48	.19	0.10	16.22	116.0	34.2	34.5	125.9
19.83	.20	0.11	14.01	154.9	-38.8	-39.5	148.9
22.21	.15	0.11	18.46	146.2	-113.3	-114.3	105.1
24.81	.10	0.14	19.94	142.8	170.8	170.2	139.2
14.41	.20	0.15	12.81	171.7	94.6	95.2	140.2
14.49	.09	0.11	14.74	133.1	21.3	21.0	104.3
22.80	.05	0.09	19.44	80.8	-54.8	-54.3	82.3
23.32	.10	0.10	19.30	179.7	-129.7	-129.3	78.0
17.71	.10	0.15	30.65	160.7	154.9	155.7	-16.9
18.60	.15	0.11	18.74	144.4	79.2	79.8	-162.4
14.23	.30	0.30	13.76	88.8	3.7	4.5	99.6
15.56	.26	0.30	16.14	54.1	-70.3	-69.4	43.3
19.00	.17	0.27	20.31	-19.0	-145.9	-144.3	-102.8
12.90	.10	0.20	27.01	-58.7	138.1	140.7	-133.6
17.20	.25	0.20	28.54	-103.0	64.4	65.6	25.3
17.25	.19	0.24	20.37	-97.6	-10.6	-9.5	-103.5
13.41	.20	0.25	15.86	-147.4	-86.7	-85.2	170.9
16.90	.31	0.33	21.53	-169.6	-160.3	-158.4	164.2
16.80	.25	0.20	25.37	-96.5	125.6	126.5	-133.1
25.28	.22	0.23	23.05	-134.6	50.0	50.4	51.9
20.14	.25	0.25	26.70	-102.3	-27.9	-25.8	-117.8

```
   .84   87.81   88.98     .72  -150.6   104.6   134.3    54.2
   .86   88.94   90.45     .91    -9.1  -142.0  -137.8  -113.7
   .96   78.95   77.70     .90   136.6    23.7    26.9    91.0
   .75   71.67   71.43    1.03   -83.1  -163.8  -164.0   -86.6
   .98   52.79   52.97     .62    45.7   -12.8   -10.2   105.1
   .75   31.40   32.85     .83   150.7   128.9   116.1   -88.7
 11.53     .86    1.10   11.92   -65.6   109.1   105.5    90.5
 12.39     .70     .81   16.47   122.0   111.8   106.1   -92.1
  8.93    1.40    1.45   10.13    91.8   163.7   158.1    60.5
 28.89     .70     .58   25.84    81.8  -131.3  -138.1   -99.0
 10.15    1.30    1.39   10.03     2.4   -49.0   -56.2    83.8
  8.08    1.30    1.30   10.88    47.5    28.7    25.5  -168.1
 11.25     .90    1.26   12.35   126.3   122.0   113.1   -73.0
 12.65    1.02     .97   10.79   105.1  -145.4  -152.0    89.3
 11.43     .96    1.00   11.70  -102.3   -58.4   -63.8   172.6
 13.54     .80     .85   14.06    -4.7    30.6    24.6  -106.1
 14.83     .90     .96   17.01  -157.9   119.8   111.8  -171.4
 17.34     .85    1.20   17.21  -179.7  -155.6  -162.3     2.6
 13.74    1.20    1.30   15.21    19.8   -79.2   -86.1    17.7
  9.08    2.25    1.49    6.05   -44.1   -21.4   -27.4  -164.5
  2.94    2.36    1.92    4.47   102.1    13.6     -.7    11.6
```

```
 15.09    -.06   -0.05   16.02   108.9  -140.0  -140.2   126.7
 30.82    -.05   -0.05   20.28  -135.5   174.8   174.5  -170.7
 18.58    -.03   -0.05   13.97  -179.6   129.7   129.5   156.8
 13.28    -.05   -0.05   12.17   177.2    83.7    83.0   145.6
 13.16     .05   -0.05   12.24   141.1    38.1    37.2    99.7
 12.81    -.05   -0.01   15.70   124.5    -8.3    -9.9    69.2
 14.34     .00   -0.04   20.53    93.6   -55.3   -55.7     4.3
 15.07     .00    0.10   24.67    73.7  -101.9  -102.7  -116.6
 15.10     .08    0.15   18.76    41.8  -149.5  -151.0   170.3
 13.02     .21    0.70   12.90    11.8   162.3   159.0   102.3
  9.46     .95    3.10   11.21   -58.4   112.3   112.1    29.0
  9.55    4.65    3.20    6.64  -139.7    69.5    96.6   -62.1
 13.00    2.21    0.67    7.73   164.4    55.3    49.2  -177.2
 19.77     .51    0.20   12.85    73.3     4.0    -0.1    73.7
 47.47     .10    0.06   17.81  -101.4   -46.7   -49.3   -15.8
 25.71     .09    0.03   15.10  -116.8   -95.5   -96.6   -87.5
 29.17     .10    0.05   18.08   -33.5  -142.5  -143.5  -117.6
 28.38     .10    0.05   16.71  -129.8   173.3   171.8  -171.4
 16.76     .05    0.02   22.72   -82.5   126.2   125.2  -138.2
 22.48     .05   -0.02   26.39  -118.6    78.5    77.4   106.4
 13.24     .15    0.10   18.52  -124.7    32.2    31.4  -103.4
```

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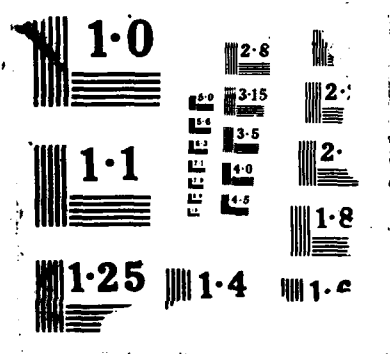AD-A193 447   THE DE-EMBEDMENT OF NETWORK-ANALYZER MEASUREMENTS(U)   1/1
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